清华大学公共管理学院产业发展与环境治理研究中心

重大联合研究项目结题报告中文摘要

追溯全球价值链里的中国碳排放

Tracing China's CO2 Emissions in Global Value Chains

孟渤[1], 王直[2], 薛进军[3], 高宇宁[4]

2014 年 12 月 8 日

1. 研究员，亚洲经济研究所，日本贸易振兴机构
2. 国际经济学家，美国国际贸易委员会
3. 教授，日本名古屋大学经济学院
4. 助理教授, 清华大学公共管理学院

*The views in the report are solely the authors' own opinion. It is not meant to represent in anyway the views of the U.S. International Trade Commission and IDE-JETRO or any of its individual Commissioners.

联合研究参与机构

- 清华大学公共管理学院产业发展与环境治理研究中心
- 日本贸易振兴机构亚洲经济研究所
- 美国国际贸易委员会经济办公室
- 名古屋大学国际低碳经济研究所

研究团队

- Alan FOX,美国国际贸易委员会，国际经济学家
- 孟渤,日本亚洲经济研究所，国际投入产出分析处副处长，研究员
- Glen PETERS,挪威国际气候环境研究中心，高级研究员
- 裴建锁，对外经济贸易大学，国际经济贸易学院，副教授
- 薛进军，名古屋大学经济学院教授，国际低碳经济研究所联席所长
- 邹乐乐，中国科学院科技政策与管理科学研究所，副研究员
- 郭琳，对外经济贸易大学，国际经济贸易学院，助理教授
- Tsubasa SHIBATA，日本亚洲经济研究所，研究员
- 刘宇，中国科学院科技政策与管理科学研究所，副研究员
- 高宇宁，清华大学公共管理学院，助理教授
- 王直，美国国际贸易委员会，领衔国际经济学家

研究顾问

- 胡鞍钢，清华大学公共管理学院，教授
- 陈玲，清华大学公共管理学院产业发展与环境治理研究中心副主任
- Robert KOOPMAN,WTO 首席经济学家；美国国际贸易委员会原运营总监
- Satoshi INOMATA，日本亚洲经济研究所，高级调研员
- 王飞 对外经济贸易大学，国际经济贸易学院，教授

项目协调员

- Akiko SASAKI，日本亚洲经济研究所
- Masahiro MORINAGA，日本石油天然气金属矿物质机构，北京所长
- 高宇宁 清华大学公共管理学院，助理教授

研究助手

- 周美芳，北京理工大学，经管学院，博士生
- 于淼，清华大学公管学院，硕士生
- 尤默，名古屋大学经济学院，博士生
- 李晓凤，北京航空航天大学，硕士生
- 胡晓红，北京理工大学，经管学院，博士生
- 吕颖康，中国农业大学，经管学院，博士生
- 郑云峰，清华大学，公管学院，博士生

目　录

引言 1

第一章追溯全球价值链里的二氧化碳排放 19
(Bo MENG, Glen PETERS and Zhi WANG)

第二章中国国内价值链与地区间的碳排放转移 122
(Lin GUO, Jinjun XUE, Bo MENG)

第三章产业分工、需求溢出与碳排放：地区异质性的全球价值链视角 179
(Jiansuo PEI, Bo MENG, Fei WANG, Jinjun XUE)

第四章企业异质性对中国碳足迹估算的影响 207
(Yu LIU, Bo MENG, Yuning GAO, Li Xiaofeng)

第五章碳税与能源税的环境经济效果：动态可计算一般均衡分析 252
(Lele ZOU, Jinjun XUE, Alan FOX, Bo MENG, Tsubasa SHIBATA)

第六章火力发电运行管理标准的环境经济效果分析 300
(Yu LIU, Xiaohong HU)

第七章环境损失对中国经济增长及全要素生产率的潜在影响 330
(Yuning GAO, Yunfeng ZHENG, Angang HU)

一. 课题概要

中国在成为世界第二大经济体和第一大进出口贸易国的同时，也成为全球温室气体排放第一大国和环境污染大国。目前，中国正在中共十八大精神的指引下实施“十二五”规划，通过发展绿色低碳经济，为实现新常态下经济发展模式根本转变而努力。因此，节能减排和保护环境不仅是来自国际社会的压力，更主要是出于自身经济社会发展的需要，以及公众对提高发展质量的诉求。从这个意义上讲，节能减排和保护环境是中国可持续发展的关键所在，也是当前社会政治稳定的迫切需要。

21 世纪是一个全球化的时代，国际分工的不断深化不仅对国际贸易和投资政策的制定，同时也对国际环境治理带来了重大挑战。中国自加入 WTO 后迅速融入国际化分工的大潮，成为全球价值链里不可或缺的重要组成部分。全球价值链在产生价值的同时，也伴随着大量的副产品，比如温室气体和污染物排放。中国的环境问题与其参与全球价值链的程度、方式以及所处的位置有着密不可分的联系。本研究将全球价值链研究的前沿成果,与环境经济学、国际贸易理论的学术洞见整合在一起，利用国际环境投入产出模型，系统地分析全球价值链与温室气体排放之间的内在关系，在提出新的学术研究方法和观点的同时，为中国的绿色发展提供理论依据和实证结论。

本研究的最终目标是要建立一个基于全球价值链的经济、环境、能源、污染物排放的综合核算体系。为此，本课题从国际、国内、产业、企业以及时间层面追溯中国在全球价值链里的碳排放，厘清生产者和消费者的排放责任，为国际碳排放核算和减排谈判以及国内节能减排政策的具体实施提供实证支持。本课题的科学研究目的是为有关部门建立中国的绿色国民经济核算体系提供理论支撑；政策研究目的是分析国内分地区、分产业、分企业的碳排放源，确定各方的减排责

任，并在此基础上进行政策模拟分析，创建一个可视化的环境政策空间效果地图，以求提高节能减排、治理环境污染政策的可操作性。

二.　研究背景

2010 年，中国的 GDP 总额超过日本成为世界第二，2013 年，中国的进出口贸易超过美国成为世界第一，我们在自豪这些成就的同时，也应看到，中国的人口只占世界人口的 19%，制造业产值只占世界制造业总额的 13%, 二氧化碳排放却占世界总量的 27%（2012 年，IEA，2014），成为国际社会抨击的对象（尽管人均排放较低）。同时，中国的二氧化硫等主要污染物排放也是世界第一。2013 年，大气污染成为高度关注的国际问题，雾霾笼罩中国五分之一国土，形成全球最大规模的环境灾难。近些年，中国的民众主要关注对象已经越来越转向健康安全、污染防治等许多同环境直接相关的问题。可以说，环境问题已成为中国社会新的不稳定因素，而过多的二氧化碳排放、过快的能源消费和能源进口增长，即影响国际能源市场价格形成，也涉及中国能源安全问题，从而成为引发国际摩擦的重要因素。中国的碳排放、环境污染的根本原因在于中国的以追求脱贫、经济发展优先为目标的低层次发展理念，以高耗能高排放为特征和以制造业为主的产业结构、在全球价值链处于低端地位、以煤炭为主的污染型能源结构。因此，目前的治理污染，节能减排政策和政府主导的投资带动式的治理方式，还没有找到治理碳排放源、环境污染源的根本。

中国不仅面临着日益趋强的环境约束，同时也在承受国际社会的批判和减排压力。中国是排放大国，国际社会要求中国减排也在情理之中。但问题是：在没有理清国际分工中各种排放在生产和消费之间关系的情况下，我们并不能确定中国在参加全球价值链的过程中到底为谁，通过哪些链条，“净排放”了多少？“共同但有区别的责任”如何在价值链上界定？而这个问题，国际社会应当搞清楚,才能就

环境治理达成共识，中国也有必要搞清楚，才能正确应对。如果不探究全球价值链与碳排责任的内在联系，在国际环境治理中，既有可能损害本国利益也有可能损害贸易伙伴国的利益。这一点有必要弄清楚。

中国政府制定了自主减排的40-45%的目标（到2020年，中国单位GDP二氧化碳排放将比2005年下降40%-45%），为了实现这些承诺，“十二五”规划中制定了节能16%和减排17%的目标，发改委也将指标按各地区的经济发展水平分解到各个行业和地区。但是，中国在向各行业和地区分摊排指标时，没有充分考虑各产业各地区在国内，国际价值链上的位置，生产技术以及节能减排技术的差异性，这可能会影响减排目标的合理和可行性，难以规避排放天堂的出现或国内省间的排放泄漏现象。

与之密切相关的问题是这些污染、资源耗竭的经济成本是什么。如果考虑到泄露，各地区和行业真实的价值形成又是什么？现行的基于名义GDP的国民经济核算体系存在严重缺陷，不仅没有扣除自然资产损失，而且将其中过度开采资源和能源，特别是不可再生资源（所产生的价值），（作为）附加值计算在GDP总量之中。这就人为地夸大了经济收益，它是以资源的急剧消耗和环境的严重退化为代价的，必将导致真实的国民福利大为减少，因而必须要对现有的国民核算体系进行校正（胡鞍钢，2005）。

2014年11月，中美在北京APEC会议上达成新的共识并发表《中美气候变化联合声明》，习近平主席和奥巴马总统宣布了各自在2020年后应对气候变化行动目标，习近平主席首次提出中国计划将二氧化碳排放峰值控制在2030年左右，并尽早实现。与此同时，中国还开始实施“能源革命”，将大幅度降低煤炭使用，并计划2030年前将非化石能源在一次能源消费中的比例提高至20%左右。这些政治许诺，为今后中国的节能减排提出了新的目标和方向，令人振奋，但是，要实现这

些承诺，还需要坚实的理论研究并制定切实可行的政策。本研究就是要在科学研究的基础上，为中国的政策制定提出一些理论依据。

三. 研究目的

以上问题既迫切又复杂，涉及环境科学、环境治理、国际贸易理论、全球价值链理论以及国民经济核算诸多领域，没有任何一个领域可以单独给出答案。本研究的目的是整合以上各领域的最新研究成果，建立一个基于全球价值链的环境、能源、污染物排放的综合核算体系。并根据该核算体系，从国际、国内、产业、企业以及时间层面追溯中国在全球价值链里的各类排放和污染源，找出平衡生产和消费者责任，支持绿色GDP核算，绿色生产率核算的新方法。同时，利用基于全球价值链的空间动态可计算一般均衡模型进行政策模拟分析，创建一个可视化环境政策空间效果地图，以求为政府优化国内的减排政策，提高减排政策的可操作性，实现中国在环境约束下的产业升级转型和可持续的绿色发展目标，提升中国在环境国际治理领域的发言权做出实实在在的贡献。我们也希望这一研究成果能为中国制定十三五规划提供参考。

四. 本研究的学术价值（摘要）

1. 我们将全球价值链研究的最前沿成果（Koopman, Wang and Wei, AER, 2014）与环境经济学，国际贸易中的隐含碳，碳足迹的学术积累相结合，试图建立一套基于国际投入产出模型，在全球价值链里同时追溯增加值和碳排放的核算体系。该体系不仅提出通过价值链上下游关系追溯碳排放的理论框架，同时通过对出口总值的分解将基于生产排放和基于需求排放的两种核算体系有机地结合在一起。通过这一核算体系，我们可以在国家，国家间，产业以及产品层面按照不同的贸易途径，系统地追溯国际价值链里增加值和碳排放的产生，分配和转移。

2. 该核算体系首次明确地提出了国际价值链里碳排放的自主责任指标。该指标是一个国家不经由任何国际贸易环节，完全为自身的最终需求所产生的碳排放。这一研究为实施联合国气候谈判“各国根据自己的能力自主制定减排目标”的最新原则提供了具体的量化指标。

3. 通过该核算体系，我们还可以科学地测算在全球价值链里获取单位价值量(GDP)所需付出的碳排放代价。为评价一个国家参与价值链的方式，程度以及其在价值链里所处的位置与碳排放之间的关系提供了科学依据。

4. 我们首次将该核算体系应用于中国国内地区层面，利用中国2007和2010年区域间投入产出模型，追溯了国内价值链里的碳排放，考察了地区间碳泄漏的程度，并且对各地区参与国内国际价值链的方式、程度及其对碳排放的影响进行了系统地分析。

5. 我们还利用反映企业异质性信息（企业所有制，贸易方式等）的中国2007年投入产出表，就中国各行业各类型企业的出口隐含碳，最终需求隐含碳从价值链的上下游关系进行了测算。

6. 我们利用数学规化模型，将中国地区间投入产出表完全内生地嵌入国际投入产出表，系统地研究了中国国内各地区在同时参与国内和国际价值链时的产业分工与碳排放之间的关系。

五. 本研究的重要发现及其政策含义

我们的研究还处在初级阶段，有一些数据还没有完全整合好，很多新的发现还没有来得及发掘，有些新观点还正在形成中，因此，很难马上提出比较成熟的政策建议。这里我们仅就当前国际社会关心和国内紧迫的问题，粗略整理一下各个研究可能引致的政策含义（不是建议），供各位专家参考。从这个意义上讲，这个课题还没有完成，需要时间去仔细分析已得到的结果，从而提炼成比较成熟的

观点，并在此基础上总结出比较可行的政策建议。

1. 一个国家的碳排放水平与其参与全球价值链的程度、方式及其在价值链中所处位置有着密切关系。我们通过对 41 个国家 1995-2009 年的数据测算发现，无论发达国家还是发展中国家，与创造的国内增加值相比，通过国际贸易获取增加值的碳排放的成本相对较高。这主要是由于近年国际分工的快速发展，带来了国际贸易中大量的高碳中间产品交易所造成的。截至目前的贸易和投资便利化政策，在促进全球价值链发展的同时，相对低估了由于国际分工、中间产品的跨国多次重复运输所带来的环境成本。全球价值链的时代，贸易和投资政策需要和环境国际治理密切结合才会有效促进全球范围内的减排目标早日实现。

2. 我们的研究表明，近年来，中国与其它发展中国家之间的碳泄露要比其与发达国家之间的碳泄漏更为严重。主要原因是第三世界国家经济发展对中国产品的需求迅速增加，同时“中国制造”对其上游的第三世界国家的高碳中间产品投入的依赖也日益加深。其结果就是两者间大量碳贸易的产生。这是亟需高度关注的问题。因为发展中国家的环境约束都相对薄弱，如果这种趋势得不到很好的管控，会对全球减排带来很大压力。从这个意义上讲， 中国应对碳泄露承担较大责任，而这一问题的解决，需要中国拿出勇气和智慧，主动发起南南合作，在提高自身节能减排步伐的同时，帮助上下游的其他发展中国家共同维护绿色价值链的发展。

3. 1995 年到 2009 年间，发达和发展中国家的碳强度都在下降，发展中国家下降的幅度更大，能效改善显著。但是，技术改善所带来的减排效果无法抵消由于经济增长所带来的碳排增加，其结果造成发展中国家的碳排放总量继续增加。中国已经承诺要在 2030 年前达到碳排放峰值，同时也应积极地为其他发展中国家早日设定合理可行的碳峰值献计献策，提供必要的资金与技术支持。

4. 中国国内地区之间的碳泄露也很严重。这主要是由于各地区参与价值链的方式、程度及其在价值链中所处的位置等决定的。考虑到各地区收入差距和经济发展状况不同，国内版本的“共同但有区别的责任”的原则也应当适应并通过政策落实，以保证落后地区在大幅度节能减排的条件下实现较快的经济发展，。

5. 我们的研究发现了一个重要问题：中国内陆欠发达地区的隐含碳出口近年增长很快。究其原因，在一定程度上是因为国家的西部开发政策和东部支持西部的协作方式促进了内陆地区的经济发展，使得这些地区通过提供大量的高碳中间产品给发达的沿海地区用作出口产品生产，间接地融入了国际价值链所造成的。因此，国内在产业转型升级的过程中需要不断强化准入门槛，统一环境标准，以免造成国内“污染避风港”的产生。

6. 近年，节能减排技术，生产技术以及消费方式的变化促进了中国各地区的减排，但是，这并没有抵消资源耗费型和产能过剩性的经济增长，最终需求结构不合理所带来的排放增加。因此，应该通过合理优化投资方式来调整最终需求结构，促进低碳投资性的高效发展方式。

7. 按生产法测算的中国碳排放的 93%来自中国企业自身的生产活动（2007年）。其中从事非加工贸易品生产的企业为主要排放大户且碳强度很高。外企的碳排放占比不到全国的 7%，相对中国企业的生产性碳排放更为环保。加工贸易由于其特殊的生产方式碳排放很少。外企在生产过程中碳排放较少，但其所带动的整个上游产业链的碳排放要高于中国企业。

8. 忽略企业异质性（企业所有制、贸易方式等）会造成对中国出口隐含碳 20%的高估，对最终需求隐含碳 7%的低估。在行业层面，传统的测算方法所造成的误差更为明显，比如电子产品行业，忽略企业异质性会造成对出口隐含碳高估 70%。

将经济普查中得到的企业属性信息与传统的投入产出统计相结合对于提高碳排放的测算精度意义重大。

9. 环境破坏造成中国产业 GDP 的潜在损失 10%左右，会拉低技术进步率 3-6%。将 GDP 进行绿化，将环境要素纳入国民经济核算体系，用自然资源的损耗价值和生态环境的降级成本以及自然资源、生态环境的恢复费用等调整现有的 GDP 指标，把它们从国内生产总值中扣除，以综合反映环境经济的变化。早日实现全国和地区层面的绿色 GDP 核算，并将其与纳入地方政府的国民经济发展目标以及干部考核指标，将会有利推动经济发展方式的转变。

10.我们利用动态 GCE 模型对碳税问题进行的研究表明， 按目前经济发展模式，中国碳排放的峰值将在 2034 年出现（这与政府的政治承诺有所不同），。但如果实施较为严格的碳税（100 元/吨）和能源税（5%），碳峰值会提前到 2032 年。结果显示：今早实行较为严格的碳税或能源税对经济增长和就业的损失会比推迟实施这些政策要小，换言之，延缓碳税的实施会对今后的减排造成更大的压力，对经济增长和就业的负面影响也会更大。

参考文献

Baldwin, R. (2011). 21st century regionalism: Filling the gap between 21st century trade and 20th century trade rules. *CEPR Policy Insight*, 56.

Ferrarini, B. and Hummels, D. eds. (2014) *Asia and Global Production Networks –Implications for Trade, Incomes and economic Vulnerability*. Edward Elgar.

Hu, A. (2011). The political economy of climate change, in Xue, J. eds. *Low-carbon Economics*, Social Science Press.

Grossman, G.M.and Rossi-Hansberg, E. (2008). Trading tasks: A simple theory of offshoring.*American Economic Review*, 98(5), 1978-97.

Koopman, R., Wang, Z., Wei, S.J. (2014). Tracing value-added and double counting in gross exports. *American Economic Review*, 104(2), 459-94.

Lenzen, M., Murray, J., Sack, F., Wiedmann, T. (2007). Shared producer and consumer responsibility – theory and practice. *Ecological Economics*, 61, pp27-42.

Lin, J., Pan, D., Davis, S.J., Zhang, Q., He, K., Wang, C., Streets, D.G., Wuebbles, D.J., Guan, D. (2014). China’s international trade and air pollution in the United States. *PNAS*, 111(5), 1736-1741.

Meng, B., Wang, Z., Koopman, R. (2013). How are global value chains fragmented and extended in China’s domestic production networks?*IDE Discussion Paper*, 424.

OECD-WTO. (2013). *Measuring Trade in Value-Added: An OECD-WTO Joint Initiative*.http://www.oecd.org/industry/ind/measuringtradeinvalue-addedanoecd-wtojointinitiative.htm

OECD, WTO and UNCTAD. (2013). “Implications of Global Value Chains for Trade, Investment Development and Jobs” prepared by OECD, WTO and UNCTAD for the G20 Leaders Summit, St. Petersburg, Russian Federation, September.

Peters, G.P., Minx, J.C., Weber, C.L., Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008. *PANS*, 108(21), 8903-8908.

Timmer, M. P., Los, B., Stehrer, R. and de Vries, G. J. (2013), Fragmentation, incomes and jobs: an analysis of European competitiveness. *Economic Policy*, 28: 613–661.

Wang, Z., Wei, S.J., Zhu, K. (2013). Quantifying international production sharing at the bilateral and sector levels. *NBER Working Paper*, 19677.

WTO-IDE. (2011). *Trade Patterns and Global Value Chains in East Asia: From Trade in Goods to Trade in Tasks*. Printed by the WTO Secretariat.

Xue, J. and Zhao, Z. eds. (2012). *Annual Report on China's Low-carbon Economic Development*, Social Sciences Academic Press.

Final Report of the CIDEG-IDE/JETRO-USITC-IGLCE Joint Project on

Tracing China’s CO^2 Emissions in Global Value Chains

Bo MENG[1], Zhi WANG[2], Jinjun XUE[3], Yuning GAO[4]

March 31, 2015

* The views in the report are those of the authors and may not reflect the views of the USITC and its Commissioners

or any other organization that the authors are affiliated with..

---

[1] Research Fellow, Institute of Developing Economies - JETRO, Japan.

[2] Lead International Economist, United States International Trade Commission, the USA.

[3] Professor, School of Economics, Nagoya University, Japan.

[4] Assistant Professor, School of Public Policy and Management, Tsinghua University, China.

Highlights on the main empirical findings and policy implications

A country's CO2 emission level is highly related to its position and participation in global value chains. More than 30% CO2 emissions in China are for fulfilling foreign final demand in 2009.

The environmental cost for generating one unit GDP in domestic production networks is lower than that through international trade for both developed and developing countries. The main driver is the high-carbon intensity trade in intermediates which has grown rapidly during the past two decades.

The carbon leakage between China and other developing economies (both are Non-Annex B members) is much severe than that between China and developed economies in 2009.

The environmental cost for generating one unit GDP shows a decreasing trend for both developed and developing countries from 1995 to 2009. However, the decrease cannot offset is the increased emission from rapid economic and population growth in emerging economies.

The carbon leakage inside China across regions is getting much serious in 2010 comparing to 2007. The principle of "common but differentiated responsibilities" should also be applied inside China across provinces for enhancing the sustainable and green growth.

The indirect embodied CO2 emissions export from China's inland regions is massive due to their deep involvement in GVCs by providing high-carbon parts and components to support coast regions' exports.

In 2007, 93% of China's production-based emissions come from Chinese Owned

Firm with high carbon emission intensity. The carbon intensity of non - processing firms is much higher than firms who engage in processing trade regardless ownership except chemical industries. Prompt duty and value-added tax free intermediate goods import, especially from Annex B countries can reduce production-based emissions in China and reduce global carbon leakage.

Foreign-owned firms do not produce much emission themselves but induce significant carbon emissions of upstream Chinese owned firms who are doing non – processing trade.

Ignoring the firm heterogeneity will overestimate embodied carbon for export by 20%, and underestimate embodied carbon for domestic final demand by 7% on national average. This bias is much higher for certain sectors (70% higher for exports of communication equipment industry).

The natural resource depletion and carbon damage cost around one tenth of China’s industrial gross value added and up to 30 per cent of fixed capital stock on average; they also lead to an average 3 - 6 per cent slowdown of the productivity growth.

The later the energy tax or carbon tax imposed, the higher the cost; postponing the carbon tax policy requires much higher tax rates, and causes greater economic loss.

The changes in carbon intensity, production technology, household’s lifestyle brought positive impacts on China’s CO2 emissions reduction between 2007 and 2010 at both national and regional levels. However, these positive factors can’t offset all the negative impacts coming from the rapid economy growth, unbalanced final demand structure.

Highlights on the academic originality of the project

Integrating two lines of research: trade in value-added/gross trade accounting and embodied emission trade/emission inventory accounting into a unified conceptual framework for the first time in the literature. This allows both value-added and emissions to be systematically traced at the country, sector, and bilateral levels thus the potential environmental cost (emission with per unit of value-added created) at each stage along Global Value Chains can be estimated. Proposed new measures (some of them are new compared to the existing literatures) clearly distinguish emissions of self-responsibility (emissions for domestic final demands without through international trade) and shared responsibility (emission through international trade) between producer and consumer located in different territories.

Introducing both Chinese regional heterogeneity (variation in regional economic size, position in production networks, industrial structure, and stages of economic development), and firm heterogeneity (firm ownership and trade mode) in tracing emissions in the domestic segment of global value chains of China. Considering such heterogeneities to reduce the “aggregate bias” inherent in IO model can improve the accuracy in estimating embodied emissions.

Using a transnational and interregional input-output data set for China to measure the production sharing, demand spillovers and CO2 emissions in both the domestic interregional and international segments of global value chains.

Taking environment costs into account by applying the genuine saving method proposed by the World Bank first time in recalculating the value added, capital formation, capital stock and related multi factor productivity for Chinese economy at the industrial level.

Joint Organization Members

- Industrial Development and Environmental Governance (CIDEG) at the School of Public Policy and Management, Tsinghua University, China
- Institute of Developing Economies-Japan External Trade Organization (IDE-JETRO), Japan
- United States International Trade Commission (USITC), the USA
- Institute of Global Low-carbon Economy (IGLCE), Nagoya University, Japan

Research Group Members

- Alan FOX , International Economist, USITC, the USA
- Bo MENG, Research Fellow, IDE-JETRO, Japan
- Glen PETERS, Senior Researcher, the Center for International Climate and Environmental Research – Oslo, Norway
- Jiansuo PEI, Associate Professor, School of International Trade and Economics, UIBE, China
- Jinjun XUE, Professor, School of Economics, Nagoya University, Japan
- Lele ZOU, Associate professor, Institute of Policy and Management, Chinese Academy of Sciences, China
- Lin GUO, Assistant Professor, School of International Trade and Economics, UIBE, China
- Tsubasa SHIBATA, Research Fellow, IDE-JETRO, Japan
- Yu LIU, Associate professor, Institute of Policy and Management, Chinese Academy of Sciences, China
- Yuning GAO, Assistant Professor, School of Public Policy and Management, Tsinghua University, China
- Zhi WANG, Lead International Economist, USITC, the USA

Research Advisors

- Angang HU, Professor, School of Public Policy and Management, Tsinghua University, China
- Lin CHEN, Vice Director, CIDEG, Tsinghua University, China
- Robert KOOPMAN, Chief Economist, The World Trade Organization, former Director of Operations, USITC, the USA

- Satoshi INOMATA, Chief Senior Researcher, Development Studies Center, IDE-JETRO, Japan

Project Coordinators

- Akiko SASAKI, Research Management Office, IDE - JETRO, Japan
- Masahiro MORINAGA, Director, JOGMEC, (former coordinator in IDE-JETRO), Japan
- Yuning GAO, Assistant Professor, School of Public Policy and Management, Tsinghua University, China

Research Assistants

- Jianguo WANG, Master’s Student, Hunan University, China and Chiba University, Japan
- Meifang ZHOU, Ph.D. Student, School of Management and Economics, Beijing Institute of Technology
- Miao YU, Master’s Student, School of Public Policy and Management, Tsinghua University
- Mo YOU, Ph.D. Student, School of economics, Nagoya University, Japan
- Xiaofeng LI, Master’s Student, Beihang University
- Xiaohong HU, Ph.D. Student, School of Management and Economics, Beijing Institute of Technology
- Yingkang LV, Ph.D. Student, College of Economics & Management, China Agricultural University
- Yunfeng ZHENG, Ph.D. Student, School of Public Policy and Management, Tsinghua University

Contents

Introduction 1

Chapter 1 Tracing CO2 Emissions in Global Value Chains 19

(Bo MENG, Glen PETERS and Zhi WANG)

Chapter 2 CO2 Emissions Transfer in China's Domestic Value Chains 122

(Lin GUO, Jinjun XUE, Bo MENG)

Chapter 3 Production Sharing, Demand Spillovers and CO2 Emissions: The case of China's Regions in GVCs 179

(Jiansuo PEI, Bo MENG, Fei WANG, Jinjun XUE)

Chapter 4 Firm Heterogeneity in Measuring China's Carbon Footprint 207

(Yu LIU, Bo MENG, Yuning GAO, Li Xiaofeng)

Chapter 5 The Emission Reduction Effect and Economic Impact of an Energy Tax vs. a Carbon Tax in China: A Dynamic CGE Model Analysis 252

(Lele ZOU, Jinjun XUE, Alan FOX, Bo MENG, Tsubasa SHIBATA)

Chapter 6 Assessing the Economic and Environmental Impacts of Raising China's Emission Standard for Thermal Power Plants: An CGE Model-Based Analysis 300

(Yu LIU, Xiaohong HU,Bo MENG)

Chapter 7 Input–Output-Based Genuine Value Added and Genuine Productivity in China’s Industrial Sectors (1995-2010) 330

(Yuning GAO, Yunfeng ZHENG, Angang HU)

Introduction

1. Background

Given the increasing sophistication of production sharing arrangements across countries among different firms, it has become increasing difficult to know "who produces what for whom exactly in the world economy". As more and more intermediate goods and services, such as parts and components, are produced in sub-sequential stages located in different countries, "Trade in Tasks" has become an important form of trade between countries (Grossman and Rossi-Hansberg, 2008). Each country or region engages at different stages of a production chain, and the value added is created and accumulated in each segment after a set of tasks are completed, thus forming a new concept called "Trade in Value-added". This is also why the former WTO director-general, Pascal Lamy prefers to use "Made in the World" (WTO-IDE, 2011, OECD-WTO, 2012) rather than "Made in USA" or "Made in China" as a new label to explain today's world trade.

Firms that are expanding their cross-border activities and trade task each other have brought dramatic changes to the global economy during the last two decades. This development is explained by the so-called second unbundling (Baldwin, 2011). The IT revolution has enabled the international unbundling of factories and offices, which means that tasks can also be traded globally. As a result, developed countries tend to be engaged in high-end and intangible production activities, such as pre-production of R&D, design, brand building, and post-production of services, marketing, while developing countries tend to focus on low-end and tangible production activities such as manufacturing, assembly and so on, because of the difference of comparative advantages across countries. This second unbundling makes countries with different resource endowments be located in different positions on the so-called “smiling curve” in global value-Chains (GVCs).

The rapid expansion of GVCs brought dramatic changes in the process of industrialization. Developing economies do not need to build a whole course of production capacity in order to achieve industrialization, they are able to use their comparative advantages to concentrate in a specific segment of a production process, thus integrate into the global economy. Participation in GVC provides developing countries the opportunities of transferring massive rural labor force to industrial and service production as well as technology spillover thus provide a new and rapid path of modernization as exampled by China’s recent experience.

However, such a path of rapid industrialization also often company with serious side effects, the most notable ones are uneven income distribution and environment deterioration in many developing countries. For instance, when looking at the CO_2 emissions created in GVCs, the “smiling curve” may become “crying curve”, because the tangible production activities concentrated in developing countries always emits more emissions comparing to the intangible production activities specialized in developed countries. If developing countries lacks of the emission related regulations and policies, significant risk of carbon leakage may occur from the rapid industrialization resulted from participation of GVC and the deepening of international fragmentation production. Most studies on GVCs focuses on the creation and distribution of value-added, employment opportunities and income (OECD, 2013, Timmer et al. 2013, Ferrarini and Hummels, 2014). However, this is just one side of GVCs. On the other side, greenhouse gas emissions and pollutions are also generated along GVCs. A recent research (Lin et al, 2013) shows that 12-24% of sulfate concentrations over the western United States on a daily basis is due to the export-related Chinese pollution. Such greenhouse gas emissions and pollutions have significantly impact on environment; an interesting finding by Lenzen et al. (2012) discovered that about 30% of global species threats are due to international trade.

In today's world economy, it is difficult to consider that a country can be independent to GVCs. As a result, a share of a country's value added (VA) or emissions generated from the production of exported products which is used to fulfill foreign final demand directly and indirectly has been increasing for both developed and developing economies. The converse is that a country's final consumption causes emissions in other countries by importing foreign goods and services. These effects are not marginal and are growing over time, The net emission transfer (production minus consumption) via international trade from developing countries to developed countries increased form 0.4 Gt CO_2 in 1990 to 1.6 Gt CO_2 in 2008, which exceeds the Kyoto Protocol emission reductions (Peters et al., 2011). All these facts clearly imply that a country's emission level from both producer and consumer's perspectives is crucially subject to its position and the extent of its participation in GVCs through international trade directly or indirectly.

Given the rapidly evolving global economic landscape, a number of questions surrounding sustainability and green growth have grown in importance. Namely, 1) who produces emissions, who ultimately consumes the products that generate these emissions, and how do GVCs tie the emitter and consumer together; 2) how does a country's position and participation in GVCs affect its emissions; 3) how should one measure the environmental cost of fragmentation production that is the economic foundation of globalization; 4) and how the responsibilities of consumers and producers for emissions in GVCs can be properly assessed.

2. Research objectives

As mentioned before, the increasing complexity in GVCs brought great challenges to not only the economic but also environment policymaking and international governance, since emissions and pollutions are the by-product in value creation process along every stage of GVCs. One of the most important things before any environment policy discussion is to accurately measure in what extent the cross country production sharing and fragmentation impact on both value creation and emissions generation, because "You can't manage what you can't measure".

The first objective of the project is to build an interdisciplinary research

framework to integrate both the existing environment-related approaches and the most recent innovative GVCs-related analytical tools (Koopman, Wang and Wei, 2014). Such a framework will help us obtain deep and consistent insights regarding to the relationship between value-added and CO_2 emissions along each stage of GVCs and better address the questions listed above.

The second objective of the project is to apply this framework to trace China's CO2 emissions in both the domestic and international segments of GVCs. Without in depth analysis on China, we can't fully understand the details and significance of current international transfer of CO_2 emissions because China is the largest "factory" economy and the largest emitter of CO_2 emissions (2009) in the world. In 2010, China's nominal GDP surpassed that of Japan, becoming the second largest economy in the world. However, China has also paid a great environmental cost during the period of its rapid economic growth, including pollution in air, water, soil, noise and CO_2 emissions, which are considered the primary source of greenhouse gases (Xue et al., 2012), causing health problems and decreasing people's quality of life. China also leads in CO_2 emission intensity (CO_2 emissions per unit GDP at constant prices) with a rate more than 6 times larger than that of the OECD countries in 2008. Therefore, China has been referred to as the "Black Cat" (Hu, 2011). Even looking at the relationship between per capital GDP and CO_2 emissions, China has also been considered as a "high-carbon" economy (Xue et al., 2012). Due to the importance of China in terms of its position and participation in GVCs, the management of China's or China related CO_2 emissions can make a significant contribution to the world CO_2 emissions reduction, in other words, “One small step in China, one giant leap for the world”.

When focusing on China’s environment related issues, two important perspectives can’t be ignored: regional and firm heterogeneities. Compared to small countries, China is the world second largest economy with significant difference among its domestic provinces. For example, the economic scale of the largest province of China (Guangdong) is close to Mexico’s total economic size in terms of GDP. The most important feature of Chinese economy is the differentials in industrial structure, production technology, energy-use efficiency, income level and overseas dependency across its domestic regions (provinces). GVCs are supported not only by domestic regions which export goods and services to the world market directly, but also by other domestic regions that participate in the global economy indirectly through domestic supply chains when they provide parts, components, and intermediate services to export-oriented regions. In order to better understand how GVCs are fragmented and extended inside China, and how a domestic region’s position and participation in GVCs impact on its CO_2 emissions, a domestic-regional perspective is necessary. In addition, local governments in China are powerful and they are the actual executors of the central government’s environmental policies. They have great interest in understanding how and where their regions participate in GVCs and how they might enhance their local industry and firms in ways that deliver more local value added, employment, and income with less CO_2 emissions. A better understanding of how GVCs impact domestic regions can help local government to develop more effective responses to the challenges of rapid globalization and the pressure coming from the requirement of CO_2 emissions reduction. A deep analysis by applying the newly developed accounting framework to China's domestic regions will generate policy related insights for both central and local governments in China.

Firm heterogeneities are another important feature of Chinese economy. Compared to other large countries, Chinese economy has much variation in terms of the firm ownership and trade modes (processing trade vs. non-processing trade in addition to exporter v.s. non-exporter, see Wang et al., 2014). Due to global economic integration, carbon emissions information at the national and industry level can no longer meet our policy demands for responding the international challenges. For example, is Chinese owned firm or foreign-owned firm in China the heaviest emitter? Which one has higher energy consumption and emission intensity? How many emissions will state-owned firms produce when providing intermediate inputs for foreign-owned firms? Introducing firm heterogeneity information to our accounting system for China will not only improve the accuracy in measuring China's CO_2 emissions in its domestic and international segment of GVCs, but also provide valuable information to help policy maker develop incentive specific environment regulations and policies.

The third objective of the project is to take advantages of the measuring results on the relationship between CO_2 emissions and GVCs to make better policy recommendations for China's green and sustainable growth as well as international environment governance. To achieve this, three types of economic models are used. The first one is the widely used CGE (Computable General

Equilibrium) model which can analyze how environment related fiscal policy and regulation affect the reduction of CO_2 emissions and the economic growth in China simultaneously. The second one is an input-output model based factor decomposition analysis. It quantifies the roles of economic growth, technology change, inter-regional spillover, and consumer preference change in determining China's CO_2 emissions and carbon intensity. The third one is an econometric model to estimate China's green growth rate and genuine total factor productivity (GTFP). Main conclusions from these models are summarized in section 4.

3. Research strategy and process

As shown in the figure below, in order to conduct this interdisciplinary, multipurpose research project, a step-by-step and consistent approach is adopted. First, we take advantages of the most recent innovative work of (Koopman, Wang and Wei, 2014) and integrate it with the existing environment related literatures to build a unified accounting framework for tracing value-added and emissions in GVCs at the country, sector, and bilateral levels through different routes of international trade consistently.

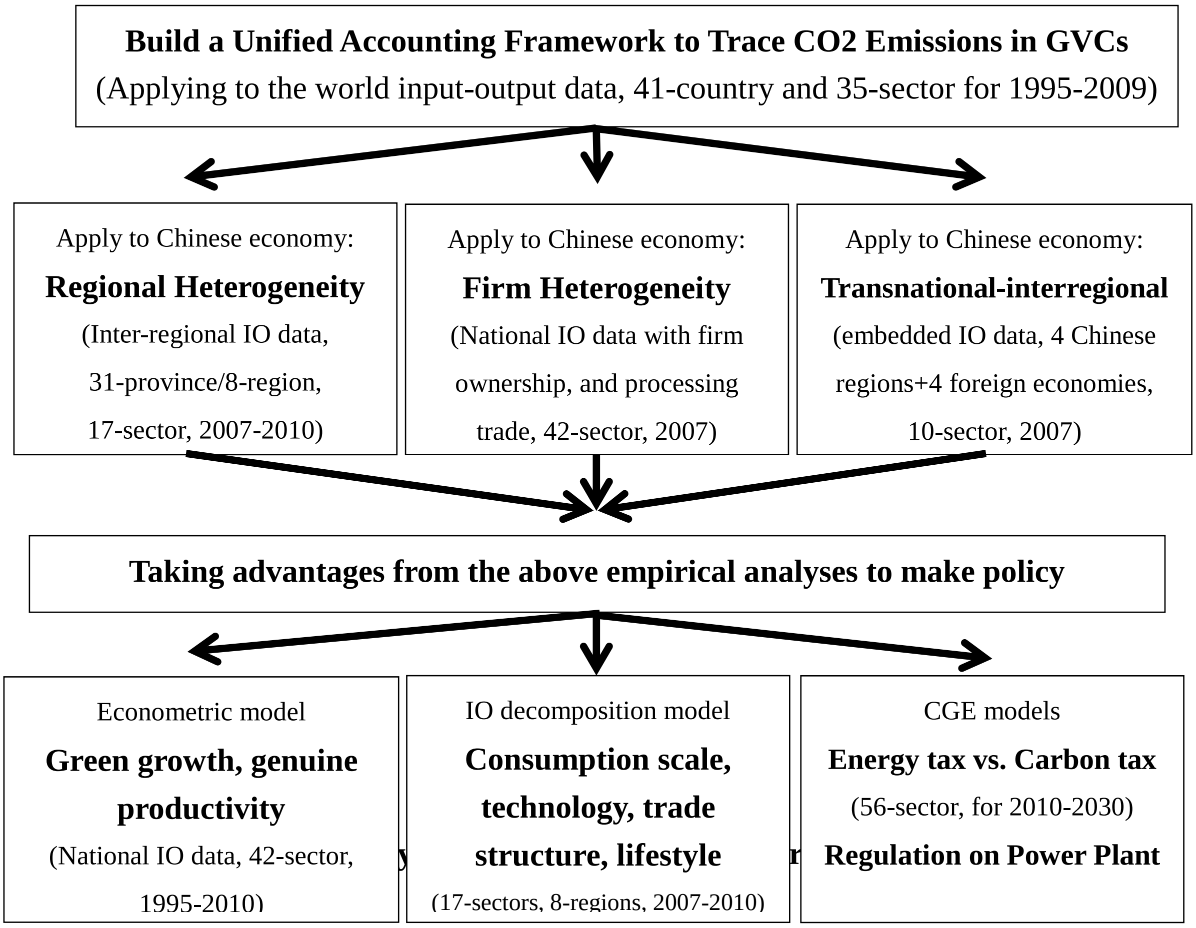
Then we apply this unified accounting framework to the World Input-Output Database (41 economies, 35 sectors, 1995-2009) to trace China CO_2 emissions in GVCs. Empirical results helped us get better understanding on "who produce emissions for whom", the relationship between China's GVC participation and its CO_2 emissions, the environmental cost of each stage of international fragmented production and so on.

In order to obtain deep insights about how Chinese regions and different types of firms engage the GVCs at the same time generate CO_2 emissions, the unified accounting framework is applied to China's interregional Input-output database (2007-2010, 31 provinces/8 regions, 42/17 sectors), China's national Input-Output table with firm heterogeneity information (2007, 135/42 sectors), China's interregional Input-Output table embedded in WIOD (2007, 4 Chinese regions, 4 foreign economies, 10 sectors; see Meng et al., 2013), respectively. The empirical results provide further detailed insights on the roles of different domestic regions and firm types have played in the process of both value-added creation and CO_2 emissions generation along various segments of GVCs; and how large and to what extent the domestic interregional carbon emissions transfer happened, as well as the potential environmental cost involved when domestic regions and firms join GVCs.

Finally, based on all the above conceptual innovation and empirical findings, three important policy issues related to China's emissions reduction and sustainable growth are studied: 1) Using an econometric model, we measure the genuine GDP growth rate and level of total factor productivity when the damages to China's environment are taken into account. The result can help policy maker to better understand the environmental cost of China's high-speed economic growth in quantitative terms; 2) The major drivers and their different roles in determining China's increasing emissions at the regional level are identified by using an Input-Output based factor decomposition model; 3) How energy/carbon tax and regulation can help reduce emissions and their negative impacts on China’s economic growth are evaluated by two CGE (Computable General Equilibrium) models.

The whole research process of the project is summarized in Figure 1 and research findings of each research step are reported in individual chapters in this report.

Figure 1 Research process



1) ***Actions must be taken to retard the increasing carbon leakage among developing economies as an organic part of the international credible and competent governance. Such south-south cooperation is essential and urgent for global emission reduction.***

Our empirical results based on data from WIOD for 41 economies, 35 sectors during 1995-2009, show that the difference in carbon intensity and the position in GVCs between developed and developing economies causes “carbon leakage” through international trade: developed economies tend to import more high-carbon intensity intermediate goods from developing economies in producing final goods and services; This kind of “carbon leakage” also happens inside non-Annex B countries, for example between the largest two developing economies, China and countries in the rest of the world. The magnitude of their bilateral CO_2 emission trade has exceeded all bilateral trade between any developed economy blocks and China (the EU-China or the US-China). This could be a great concern since both China and countries in the rest of the world are Non-Annex B economies and both have relatively weaker environmental regulations. In the case of China, prompt duty and value-added tax free on intermediate imports, especially from developed countries can reduce China’s production-based emissions and global carbon leakage at the same time, since both China’s domestic and imported intermediate goods from other developing economies embed high carbon contents.

2) ***Helping developing countries to set an appropriate emission peak in***

terms of the current self-responsibility-based emissions should be a constructive way for curbing the rapid increase of global carbon emissions.

There has been a consensus on the "Common but Differentiated Responsibilities" (CBDR) in the international community. However, about how to make effective implementation of CBDR, many challenges still remain, especially on the treatment of historical responsibility on climate change. The level of concern on the historic accumulation of CO_2 emissions generated in the era of western countries' industrialization may decrease in terms of the rapidly increasing self-responsibility-based emissions in developing countries in recent two decades. It may be relative easier to achieve consensus on the limit of self-responsibility-based emissions than allocate shared responsibilities.

3) Trade and investment policies should not be independent to environment policies in the new era of GVCs.

A decreasing trend of the environmental cost measured by "trade in CO_2 emissions" / "trade in value-added" for both Annex B and Non-Annex B countries from 1995 to 2009 has been observed in our research. Although, the pace of decrease for Non-Annex B countries is faster than that for Annex B countries, the rapid economic growth for Non-Annex B countries generate large emissions at the absolute level, that is, the decrease of environmental cost in per unit GDP is still slower than the increase of CO_2 emission from the rapid economic growth of Non-Annex countries. This implies that the past and future efforts in improving trade and investment liberalization and facilitation in both developed and developing economies may spur on absolute level of global CO_2 emissions through the following two main channels: 1) increasing carbon leakage across countries between developed and developing economies and among developing economies; 2) the increasing territory emissions consumed by developing economies themselves, if trade and investment policies only focus on value-added gain, job opportunity and firm competitiveness without adequate consideration to restrain related environment cost.

4) A policy mixture should be designed and conducted to reduce regional CO_2 emissions in China. At the same time, the order of priority when conducting policies is crucial.

We also applied the new accounting framework proposed in the project to China's domestic regions. A similar result as found for the Non-Annex B countries at the international level can also be observed among Chinese domestic regions. Namely, the environmental cost for both coastal regions (developed regions) and inland regions (developing regions) between 2007 and 2010 has decreased. However, the decrease of environmental cost in per unit GRP could not compensate additional emission generated from the increasing economic scale for all inland regions and most coast regions. More detailed empirical results show that the final demand structure, especially the large portion of capital formation is another important driver of the rapidly increased regional CO_2 emissions. On the other hand, the lifestyle change indeed brought positive impacts on the carbon reduction for all regions, especially for the largest urban area (Beijing and

Tianjin), due to the increasing share of services consumption in household’s total expenditures. However, the positive impact coming from lifestyle changes can’t offset the negative impacts from the unbalanced final demand structure for most regions (except for Beijing and Tianjin area). Policies (i.e. environment oriented public education investment) that enhance the lifestyle change to move to a more environment-friendly way are time-consuming but a very important measure for demand-driven carbon emission reduction from a long-term view. In a short to medium term, optimizing the final demand structure by using both market oriented tools such as tax, financial policies and regulation or better control on regional public investment to adjust the capital formation should be a constructive way for carbon reduction. The carbon intensity change depends on the innovation both in production technology and in energy-saving technology. Introducing ETS (emissions trading system), integrating regional ETS into national or international frameworks can give firms more market oriented incentives and options to help them engage innovation for carbon reduction.

5) ***Linking the achievement level of green GDP index with the performance evaluation system used in local government officials’ promotion process, may help local governments break away from the traditional GDP oriented high-carbon, high-pollution development pattern.***

From the perspective of green growth, our empirical results show that the natural resource depletion and carbon damage cost nearly one tenth of China’s industrial gross value added. The lost on value added fluctuated from 10 per cent in mid 1990s to 8.5

per cent in 2010, while their accumulation effect drove the lost in capital stock peaked at 30 per cent on average in 2007. They also lead to a lower sectoral level productivity growth average at 3-6 per cent in traditional measure. The over consumption of natural resource and the pollution will discount the value added growth and capital stock of industrial sectors. The application of “green GDP” accounting at both the national and regional level can help governments understand both the importance of green growth, and their environment responsibility.

6) ***The international consensus on environment related international standard (regulation) targeting on multinationals’ activities can prevent developing economies from “race to the bottom” game or falling into the “pollution haven” situation.***

By considering firm heterogeneity (firm ownership and trade mode) in the emission accounting system, our empirical results show that, in 2007, 93% of China’s production-based emissions come from Chinese owned firms with high carbon emission intensity. The carbon intensity of non - processing firms is much higher than firms who engage in processing trade regardless ownership except chemical industries. Foreign-owned firms do not produce much emission themselves but induce significant carbon emissions of upstream Chinese owned firms who are doing non – processing trade. This finding may help us provide much constructive ways for sharing the responsibility of carbon emission reduction between developed and developing economies in GVCs. One policy recommendation is to improve the international consensus mainly targeting on developed countries that requires their multinational enterprises to follow green supply chain management with the same environmental standard on their suppliers who are located in developing countries. The key point is that there should be no difference in the standard across developing countries. This can help developing countries avoid the “race to the bottom” competition game. In turn, for developing countries, they should enhance their collaboration to establish a common standard concerning environment regulations when inviting foreign investment in or being involved in global supply chains led by multinationals. This can prevent some multinationals from “pollution haven” searching.

7) ***Actions for CO2 emissions reduction need speeding up in China. The later the carbon or additional energy tax imposed, the higher the cost; postponing the carbon tax policy requires much higher tax rates, and causes greater economic loss.***

In this research, we also conducted some simulation analyses for assessing the impacts of environment related taxation and regulation on Chinese economy. Our results show that without any action (the baseline scenario), the peak of CO_2 emissions will appear in 2034 with about 10.5 Gt. With 100 RMB carbon tax plus 5% fuel tax imposed in 2015, the peak can be shifted to 2032 with about 8.8 Gt total CO_2 emissions. However, in order to achieve this goal, China has to bear 6.7% GDP loss at the national level and about 8% job loss in some high-carbon industries compared to the baseline. There is no free lunch, at the same time, we are now pressed for time since Chinese

President Xi announced to peak Chinese CO_2 emissions around 2030 at the 2014 APEC summit in Beijing.

8) Future work plan: tracing China’s pollution sources in GVCs with more detailed treatments of regional and firm heterogeneities

As a good touchstone, we applied our new accounting framework to CO_2 emissions related issues in the current research project. Given the high concern on PM2.5, exploring the linkage between CO_2 emissions and pollutant emissions, as well as tracing China’s pollution sources in GVCs should be one of the next research targets. Again, China’s regional heterogeneity is a key for better understanding the whole economic and environmental system, unmasking the domestic pollution haven hypothesis at the domestic region (province) levels can provide us deep insights on the relationship between domestic value chains and emissions (pollutions), thus support better policy making in the process of China’s industry upgrading. Finally, introducing more firm heterogeneity information, such as firm size (large and SME), ownership, and trade mode into environment policy oriented CGE models, can help us better understand how tax and regulation impact on global environment, to what extent by various routes of GVCs.

Reference

Baldwin, R. (2011). 21st century regionalism: Filling the gap between 21st century trade and 20th century trade rules. *CEPR Policy Insight*, 56.

Ferrarini, B. and Hummels, D. eds. (2014) *Asia and Global Production Networks –Implications for Trade, Incomes and economic Vulnerability*. Edward Elgar.

Hu, A. (2011). The political economy of climate change, in Xue, J. eds. *Low-carbon Economics*, Social Science Press.

Grossman, G.M. and Rossi-Hansberg, E. (2008). Trading tasks: A simple theory of offshoring. *American Economic Review*, 98(5), 1978-97.

Koopman, R., Wang, Z., Wei, S.J. (2014). Tracing value-added and double counting in gross exports. *American Economic Review*, 104(2), 459-94.

Lenzen, M., Murray, J., Sack, F., Wiedmann, T. (2007). Shared producer and consumer responsibility – theory and practice. *Ecological Economics*, 61, pp27-42.

Lin, J., Pan, D., Davis, S.J., Zhang, Q., He, K., Wang, C., Streets, D.G., Wuebbles, D.J., Guan, D. (2014). China’s international trade and air pollution in the United States. *PNAS*, 111(5), 1736-1741.

Meng, B., Wang, Z., Koopman, R. (2013). How are global value chains fragmented and extended in China’s domestic production networks? *IDE Discussion Paper*, 424.

OECD-WTO. (2013). *Measuring Trade in Value-Added: An OECD-WTO Joint Initiative*. http://www.oecd.org/industry/ind/measuringtradeinvalue-addedanoecd-wtojointinitiative.htm

OECD, WTO and UNCTAD. (2013). “Implications of Global Value Chains for Trade, Investment Development and Jobs” prepared by OECD, WTO and UNCTAD for the G20 Leaders Summit, St. Petersburg, Russian Federation, September.

Peters, G.P., Minx, J.C., Weber, C.L., Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008. *PANS*, 108(21), 8903-8908.

Timmer, M. P., Los, B., Stehrer, R. and de Vries, G. J. (2013), Fragmentation, incomes and jobs: an analysis of European competitiveness. *Economic Policy*, 28: 613–661.

Wang, Z., Wei, S.J., Zhu, K. (2013). Quantifying international production sharing at the bilateral and sector levels. *NBER Working Paper*, 19677.

WTO-IDE. (2011). *Trade Patterns and Global Value Chains in East Asia: From Trade in Goods to Trade in Tasks*. Printed by the WTO Secretariat.

Xue, J. and Zhao, Z. eds. (2012). *Annual Report on China's Low-carbon Economic Development*, Social Sciences Academic Press.

Chapter 1

Tracing Greenhouse Gas Emissions in Global Value Chains*

Bo MENG, Glen P. PETERS, and Zhi WANG

Abstract: This paper integrates two lines of research into a unified conceptual framework: trade in global value chains and embodied emissions. This allows both value added and emissions to be systematically traced at the country, sector, and bilateral levels through various routes in global production networks. By combining value-added and emissions accounting in a consistent way, the potential environmental cost (amount of emissions per unit of value added) along global value chains can be estimated from different perspectives (production, consumption, and trade). Using this unified accounting method, we trace value-added and CO_2 emissions in global production and trade networks among 41 economies in 35 sectors from 1995 to 2009 based on the World Input–Output Database, and show how they improve our understanding on the impact of cross-border production sharing on the environment.

Key Words: trade in value-added; embodied emissions; global value chains; environmental analysis; input–output analysis; international trade; carbon intensity

JEL Number: E01, E16, F1, F14, F18, Q5, Q54, Q56

* Meng (Institute of Developing Economies, JETRO, Japan); Peters (Center for International Climate and Environmental Research – Oslo (CICERO), Norway); and Wang (US International Trade Commission, Washington, D.C.). The views in the paper are those of the authors and may not reflect the views of the USITC and its Commissioners or any other organization that the authors are affiliated with. We thank Prof. Jinjun Xue (Nagoya University, Japan) and Dr. Kunfu Zhu (Chinese Academy of Sciences) for discussions related to this work and IDE-JETRO's peer reviewer, Dr. Masami Ishida for his comments on an earlier version of the draft. We are grateful for the financial support from CIDEG, Tsinghua University. Zhi Wang also acknowledges the research support from Stanford Center for International Development.

1. Introduction

The rise of global value chains (GVCs) during the last two decades has significantly changed the nature and structure of international trade, with many new implications for policy (Baldwin, 2012; Timmer et al. 2013). Studies on GVCs have covered a variety of topics such as vertical specialization (Hummel et al. 2001), trade in tasks (Grossman and Rossi-Hansberg 2008; Baldwin and Robert-Nicoud 2014), magnification of trade cost from multi-stage production (Yi 2010), value chain organization (Antras and Chor 2013) as well as the measurement of the creation and distribution of employment and income in GVCs (OECD et al. 2013; Timmer et al. 2014b; Ferrarini and Hummels 2014).

In recent years, however, many scholars have turned their attention to the interaction of GVCs and environmental policies (Hoekstra and Wiedmann 2014). A large body of literature has developed to assess “consumption-based accounting” of historical emissions (Tukker and Dietzenbacher 2013). This literature adjusts the standard territorial-based emission accounts by removing the emissions associated with the production of exports and adding the emissions associated with the production of imports (Peters and Hertwich 2008). Most early studies focused on climate policy. It has been found that international trade accounts for one-quarter of global carbon emissions, but the contributions of exports to a country’s territorial emissions (median 29%, range 8–64%, year 2007) and imports to a country’s consumption-based emissions (median 49%, range 6–196%, year 2007) are significant (Andrew and Peters 2013). Developed nations collectively have higher consumption-based emissions than territory-based emissions, meaning that they are net importers of emissions and thereby benefit from environmentally intensive production abroad (Davis and Caldeira 2010; Peters et al. 2011; Arto and Dietzenbacher 2014).These effects are growing over time, and the net transfer of emissions (production minus consumption) via international trade from developing countries to developed countries increased from 0.4 Gt CO_2 in 1990 to 1.6 Gt CO_2 in 2008, which exceeds the emissions reductions obtained within the Kyoto Protocol (Peters et al. 2011). The same conclusions have been reached for many environmental issues, such as energy (Davis et al. 2011), air pollution (Lin et al. 2014), material use (Wiedmann et al. 2013), land use (Weinzettel et al. 2013), biomass (Peters et al. 2012), water (Hoekstra and Mekonnen 2012), and biodiversity (Lenzen et al. 2012). For example, Lin et al. (PNAS, 2014) shows that 12-24% of sulfate concentrations over the western United States on a daily basis is due to the export-related Chinese pollution, and Lenzen et al. (Nature, 2012) discovered that about 30% of global species threats are due to international trade.

The research on consumption-based accounting of environmental impacts has considerable methodological and conceptual overlap with the work on trade in value added (Johnson and Noguera, 2012, Koopman et al. 2014, Timmer et al. 2014b), but so far there has been very little attempt to formally link these two independent lines of research. This is the objective of this paper.

Better understanding the relationship between emissions and GVCs requires a consistent and well-defined accounting system, which can provide proper measurements to trace value added and the amount of emissions in each stage of production and trade from different perspectives along the GVCs consistently and systemically.

In building such a unified accounting framework, existing efforts toward the measurement of embodied emissions in trade, based on multi-regional input–output (MRIO) models, provide a good starting point (e.g., Peters 2008; Peters and Hertwich 2008; Hertwich and Peters 2009; Kanemoto et al. 2012; Meng et al. 2013). These efforts have significantly enhanced our understanding of embodied emissions in trade, and provide complete account of embodied emissions in global supply chains at country aggregates. However, less attention has been paid to the difficulties to associate embodied emission associated with gross bilateral trade flows, especially at the sector/product level (Atkinson et al., 2011), thus limits its policy relevance such as border carbon tax design (Atkinson, 2013).

By integrating recent international trade literature on gross trade accounting and environment economics literature on embodied emission trade and carbon footprint, this paper makes the following new contributions:

First, we generalize existing measures of embodied emissions and consistently define trade-related embodied emission measures at country, industry, bilateral and product levels in precise mathematical terms. We also define trade in emission measure that is fully consistent with gross bilateral trade flows, overcoming incompleteness of existing measures[1].

---

[1] The existence of both Bilateral Trade Input-Output (BTIO) and Multi-Regional Input-output (MRIO) based measures in the large body of embodied emissions literature is due to two reasons: 1) when MRIO table is not available, using national IO table and international trade statistics, embodied emissions in bilateral trade can still be estimated. However, biases may occur since trade in intermediate exports is treated as exogenous variable in a BTIO model. 2) Using MRIO can remove such biases but once intermediate trade is treated as endogenous variable, the difficulty will come from how to properly allocate embodied emissions in gross intermediate trade flows. This remains unsolved in the existing

Second, by integrating with gross trade accounting methods in recent international economics literature, we are able to measure trade in value-added and trade in emissions at country, bilateral, and sector/product levels in one unified accounting framework. Such a framework is not only able to measure value-added and emissions generated from each production stage (slice the value chain), but can also identify the special trade routes by which value-added and emissions are created, transferred, and consumed. By combining value-added and emissions accounting in a consistent way, the potential environmental cost along GVCs can also be estimated (e.g. emissions with per unit of value-added created) from different perspectives (production, consumption and trade).

Third, we demonstrated that the distinction between the forward and backward industrial-linkage is the key to properly measure embodied emissions at disaggregate level. Building on decomposition techniques originally developed by Leontief (1936), we show that using the forward industrial-linkage-based decomposition, the total emissions from a country/industry can be traced according to where and by which downstream GVC routes their associated gross output are used. Using the backward industrial-linkage-based decomposition, we show that the total emissions from all upstream production stages of a final good or service in a global value chain can be fully identified. Both decomposition methods produce the same total emission estimates for a country at the aggregate level, but they differ at the sector level due to differences in measuring indirect emissions generated from production sharing arrangements.

Fourth, We follow the idea presented in the recent innovative work of Koopman et

---

literature until this paper. In this sense, we unified the two analytical frameworks into one system and enabled it to provide all emission measures derived from both MRIO and BITO in the existing literature.

al. (2014), and Wang et al. (2013), in which they decompose all bilateral intermediate trade flows according to their final destination and express gross intermediate trade flows as destination countries' final demands. Applying this technique to measure global emissions in gross exports, we present a bridge to consistently link production-based and consumption-based accounts of emissions at the regional, sectoral, and bilateral levels. We further decompose emissions generated from the production of a country's gross exports into eight different routes along GVCs as well as their relative economic benefit/environment cost ratio first time in the literature. We also separate emissions generated from production of a country's GDP into international trade related and unrelated portions, thus clearly distinguish emissions of self-responsibility (emissions from production satisfies domestic final demands without through international trade) and shared responsibility (emission from production satisfies domestic final demands through international trade) between producers and consumers located in different territories.

Finally, we report a number of applications based on the World Input–Output Database (WIOD[1]) to illustrate the potential of this new integrated accounting frameworks to deepen our understanding of the impact of global value chains on the environment. For example, by clearly distinguishing emissions generated from different GVC production routes, we find that environmental cost for generating one unit of GDP only through domestic routes is lower than that created through international trade for most G-20 countries in recent decades. The main driver is the high-carbon-intensity trade in intermediates, which has grown rapidly during the period we have data

---

[1] For detailed information, see Timmer et al. (2014a).

(1995-2009). More importantly, previous literatures emphasis emission transfers between developed and developing countries, while the ability to decompose both value-added and emission production and absorption by GVC routes enable us find such transfer also happens among developing countries, and is increasingly becoming the major source of emission transfer in the global production system, especially between China and other non-Annex B countries (developing economies). Their share in total global trade related emissions had increased dramatically from just 5% of in 1995 to nearly 20% in 2009. We also provide a number of interesting figures that clearly show a country's pattern and level of emissions is crucially subject to its position and the extent of its participation, directly or indirectly, in GVCs through international trade.

This paper is organized as follows: Section 2 presents the integrated accounting framework and defines various embodied emission measures. Section 3 presents a number of illustrative applications for tracing CO_2 emissions in GVCs. Section 4 concludes.

2. Concepts and Methodology

2.1 Embodied emissions through forward and backward industrial linkage

The methods used to estimate embodied emissions[1] are rooted in the work of Leontief (1936). Leontief demonstrated that the complex linkages among different industries across countries can be expressed as various inter-industry, cross-country transactions organized into chessboard-type matrices, known as IO tables. Each column

---

[1] A clarification is needed on what is meant by "embodied". The emissions embodied in gross output/final goods or exports/imports can be defined as the emissions that occur in the production of a product. The emissions are not actually a physical part of the product, but rather, are emitted in the production of the product.

in the table represents the required inputs from other industries (including imports and direct value added) to produce the given amount of the product represented by that column. After normalization, the technical coefficient table represents the amount and type of intermediate inputs needed in the production of one unit of gross output. Using these coefficients, the gross output in all stages of production that is needed to produce one unit of final products can be estimated via the Leontief inverse. When the output associated with a particular level of final demand are known, the total emissions throughout the (global) economy can be estimated by multiplying these output flows with the emission-intensity coefficient (amount of emissions per unit of gross output) in each country/industry.

To illustrate how the classic Leontief method works, let us assume a two-country (home and foreign) world, in which each country produces tradable products in N differentiated industries. Products in each sector can be consumed directly or used as intermediate inputs, and each country exports both intermediate and final products. All gross output produced by country s must be used as either an intermediate or a final product at home or abroad, that is

$$X^s = \underbrace{A^{ss}X^s + Y^{ss}}_{Domestic} + \underbrace{A^{sr}X^r + Y^{sr}}_{Exports} \quad r,\, s = 1{,}2 \qquad (1)$$

where X^s is the $N\times 1$ gross output vector of country s, Y^{sr} is the $N\times 1$ final demand vector that gives demand in country r for final goods produced in s, and A^{sr} is the $N\times N$ IO input coefficient matrix, giving intermediate use in r of goods produced in s. The superscripts in A^{sr} and Y^{sr} mean that s is the producing country and r is the destination country. In (1), $A^{ss}X^s+Y^{ss}$ is domestic use of products, while $A^{sr}X^r+Y^{sr}$ is exports to foreign countries, these in turn can be split into intermediate use $A^{ss}X^s+A^{sr}X^r$ and final consumption $Y^{ss}+Y^{sr}$. The two-country production and trade system can be written as a multi-regional IO (MRIO) model in block matrix notations

$$\begin{bmatrix} X^s \\ X^r \end{bmatrix} = \begin{bmatrix} A^{ss} & A^{sr} \\ A^{rs} & A^{rr} \end{bmatrix} \begin{bmatrix} X^s \\ X^r \end{bmatrix} + \begin{bmatrix} Y^{ss}+Y^{sr} \\ Y^{rs}+Y^{rr} \end{bmatrix}, \tag{2}$$

which shows a clear distinction between intermediate use (*AX*) and final consumption (*Y*). The intermediate use can be either at domestic market (diagonals) or exported to/imported from (off-diagonals) foreign countries, and likewise for the final consumption. In this model, the final consumption is exogenous, while intermediate use is endogenous. After rearranging terms, we have

$$\begin{bmatrix} X^s \\ X^r \end{bmatrix} = \begin{bmatrix} I-A^{ss} & -A^{sr} \\ -A^{rs} & I-A^{rr} \end{bmatrix}^{-1} \begin{bmatrix} Y^{ss}+Y^{sr} \\ Y^{rs}+Y^{rr} \end{bmatrix} = \begin{bmatrix} B^{ss} & B^{sr} \\ B^{rs} & B^{rr} \end{bmatrix} \begin{bmatrix} Y^s \\ Y^r \end{bmatrix}, \tag{3}$$

where B^{sr} denotes an $N \times N$ block matrix, commonly known as the Leontief inverse, which is the total requirement matrix that gives the amount of gross output in producing country *s* required for a one-unit increase in final demand in country *r*. The diagonal terms B^{ss} differ from the "local" Leontief inverse $L^{ss}=(I-A^{ss})^{-1}$ due to the inclusion of off-diagonal terms via the inverse operation. Y^s is an $N \times 1$ vector that gives global use of final products from country *s*, including domestic final products sales Y^{ss} and final products exports Y^{sr}.

For our later sector level analysis, it is worthwhile to break Equations (2) and (3) into sectoral details. For N=2, this can be re-written by element as follows:

Domestic IO Coefficients

$$\begin{bmatrix} x_1^s \\ x_2^s \\ x_1^r \\ x_2^r \end{bmatrix} = \begin{bmatrix} a_{11}^{ss} & a_{12}^{ss} & a_{11}^{sr} & a_{12}^{sr} \\ a_{21}^{ss} & a_{22}^{ss} & a_{21}^{sr} & a_{22}^{sr} \\ a_{11}^{rs} & a_{12}^{rs} & a_{11}^{rr} & a_{12}^{rr} \\ a_{21}^{rs} & a_{22}^{rs} & a_{21}^{rr} & a_{22}^{rr} \end{bmatrix} \begin{bmatrix} x_1^s \\ x_2^s \\ x_1^r \\ x_2^r \end{bmatrix} + \begin{bmatrix} y_1^{ss} + y_1^{sr} \\ y_2^{ss} + y_2^{sr} \\ y_1^{rs} + y_1^{rr} \\ y_2^{rs} + y_2^{rr} \end{bmatrix} \tag{2a}$$ [1]

Import IO Coefficients

$$\begin{bmatrix} x_1^s \\ x_2^s \\ x_1^r \\ x_2^r \end{bmatrix} = \begin{bmatrix} 1-a_{11}^{ss} & -a_{12}^{ss} & -a_{11}^{sr} & -a_{12}^{sr} \\ -a_{21}^{ss} & 1-a_{22}^{ss} & -a_{21}^{sr} & -a_{22}^{sr} \\ -a_{11}^{rs} & -a_{12}^{rs} & 1-a_{11}^{rr} & -a_{12}^{rr} \\ -a_{21}^{rs} & -a_{22}^{rs} & -a_{21}^{rr} & 1-a_{22}^{rr} \end{bmatrix}^{-1} \begin{bmatrix} y_1^{ss} + y_1^{sr} \\ y_2^{ss} + y_2^{sr} \\ y_1^{rs} + y_1^{rr} \\ y_2^{rs} + y_2^{rr} \end{bmatrix}, \tag{3a}$$

$$= \begin{bmatrix} b_{11}^{ss} & b_{12}^{ss} & b_{11}^{sr} & b_{12}^{sr} \\ b_{21}^{ss} & b_{22}^{ss} & b_{21}^{sr} & b_{22}^{sr} \\ b_{11}^{rs} & b_{12}^{rs} & b_{11}^{rr} & b_{12}^{rr} \\ b_{21}^{rs} & b_{22}^{rs} & b_{21}^{rr} & b_{22}^{rr} \end{bmatrix} \begin{bmatrix} y_1^s \\ y_2^s \\ y_1^r \\ y_2^r \end{bmatrix}$$

where each element above is now a scalar: x_j^s is the gross output of sector *j* in country *s*; y_i^{sr} represents final goods produced by sector *i* in country *s* for consumption in country *r* (*i*,*j* = 1,2); a_{ij}^{sr} is the direct IO coefficient that measures the intermediate inputs produced in sector i of country *s* that are used in the production of one unit of gross output in sector j of country *r*, and b_{ij}^{sr} is the total requirement coefficient that gives the total amount of the gross output of sector i in country *s* needed to produce an extra unit of the sector j's final product in country r. Other coefficients have similar economic interpretations.

---

[1] The elements in the diagonal block of the A matrix are domestic input-output coefficients, while elements in the off-diagonal block are import input –output coefficients. The Y matrix is similar.

Define the direct emission intensity as $f_j^c \equiv p_j^c / x_j^c$ for $c = s,r$, j=1,2, then the estimation and decomposition of the country- and sector-level production of emissions can be expressed as

$$\hat{F}\,B\hat{Y} = \begin{bmatrix} f_1^s & 0 & 0 & 0 \\ 0 & f_2^s & 0 & 0 \\ 0 & 0 & f_1^r & 0 \\ 0 & 0 & 0 & f_2^r \end{bmatrix} \begin{bmatrix} b_{11}^{ss} & b_{12}^{ss} & b_{11}^{sr} & b_{12}^{sr} \\ b_{21}^{ss} & b_{22}^{ss} & b_{21}^{sr} & b_{22}^{sr} \\ b_{11}^{rs} & b_{12}^{rs} & b_{11}^{rr} & b_{12}^{rr} \\ b_{21}^{rs} & b_{22}^{rs} & b_{21}^{rr} & b_{22}^{rr} \end{bmatrix} \begin{bmatrix} y_1^s & 0 & 0 & 0 \\ 0 & y_2^s & 0 & 0 \\ 0 & 0 & y_1^r & 0 \\ 0 & 0 & 0 & y_2^r \end{bmatrix}$$

$$= \begin{bmatrix} f_1^s b_{11}^{ss} y_1^s & f_1^s b_{12}^{ss} y_2^s & f_1^s b_{11}^{sr} y_1^r & f_1^s b_{12}^{sr} y_2^r \\ f_2^s b_{21}^{ss} y_1^s & f_2^s b_{22}^{ss} y_2^s & f_2^s b_{21}^{sr} y_1^r & f_2^s b_{22}^{sr} y_2^r \\ f_1^r b_{11}^{rs} y_1^s & f_1^r b_{12}^{rs} y_2^s & f_1^r b_{11}^{rr} y_1^r & f_1^r b_{12}^{rr} y_2^r \\ f_2^r b_{21}^{rs} y_1^s & f_2^r b_{22}^{rs} y_2^s & f_2^r b_{21}^{rr} y_1^r & f_2^r b_{22}^{rr} y_2^r \end{bmatrix} \qquad (5)$$

This matrix gives estimates of the sector and country sources of emissions in each country's final goods production. Each element in the matrix represents emissions from a source industry of a source country directly or indirectly generated in the production of final products (consumed in both the domestic and foreign markets) in the source country. Looking at the matrix along the rows yields the distribution of emissions created from one country/sector across all countries/sectors. For example, the first element of the first row, $f_1^s b_{11}^{ss}(y_1^{ss} + y_1^{sr})$, is the emissions created by sector 1 in country *s* to produce its final goods for both domestic sales and exports. The second element, $f_1^s b_{12}^{ss}(y_2^{ss} + y_2^{sr})$, is the emissions generated by sector 1 in country *s* to produce intermediate input used by sector 2 in country *s* to produce its final products. The third and fourth elements, $f_1^s b_{11}^{sr}(y_1^{rs} + y_1^{rr})$ and $f_1^s b_{12}^{sr}(y_2^{rs} + y_2^{rr})$, are, respectively, emissions from sector 1 in country *s* generated in the production of intermediate inputs used by the

1st and 2nd sectors in country *r* to produce country *r*'s final products. Therefore, summing up the first row of the matrix, we obtain the total emissions generated from sector 1 in country *s*. This can be expressed mathematically as

$$\begin{aligned} p_1^s &= f_1^s x_1^s = f_1^s (b_{11}^{ss} y_1^s + b_{12}^{ss} y_2^s + b_{11}^{sr} y_1^r + b_{12}^{sr} y_2^r) \\ &= \left[f_1^s b_{11}^{ss} y_1^{ss} + f_1^s b_{12}^{ss} y_2^{ss} + f_1^s b_{11}^{sr} y_1^{rs} + f_1^s b_{12}^{sr} y_2^{rs} \right] + \left[f_1^s b_{11}^{ss} y_1^{sr} + f_1^s b_{12}^{ss} y_2^{sr} + f_1^s b_{11}^{sr} y_1^{rr} + f_1^s b_{12}^{sr} y_2^{rr} \right] \end{aligned} \tag{6}$$

which distributes the total emissions produced in a country/industry according to where its total gross output are finally absorbed. The value of p_j^s is consistent with the production-based National Emission Inventory (NEI) according to the economic activities of residential institutions as defined by the System of National Accounts (SNA), similar to GDP by-industry statistics (de Haan and Keuning 1996, 2001; Pedersen and de Haan 2006)[1].

Looking at the $\hat{F} B \hat{Y}$ matrix down a column yields emissions estimates from all countries/sectors across the world for the production of final products in a particular country/sector. For example, the second element in the first column, $f_2^s b_{21}^{sr} (y_1^{ss} + y_1^{sr})$, is the amount of emissions generated in sector 2 of country *s* to produce intermediate inputs used by sector 1 in country *s* to produce final products, and the third and fourth elements, $f_1^r b_{11}^{rs} (y_1^{ss} + y_1^{sr})$ and $f_2^r b_{21}^{rs} (y_1^{ss} + y_1^{sr})$, respectively, are emissions generated in sectors 1 and 2 of (foreign) country *r* to produce intermediate inputs used by sector 1 in country *s* in the production of final products.

Adding up all elements in the first column gives the global emissions generated by

---

[1] For the difference between the production-based NEI estimates from the MRIO table and the UNFCCC NEI, see Peters (2008).

the production of final products in sector 1 of country s, denoted as $p(y_1^s)$, i.e

$$p(y_1^s) = (f_1^s b_{11}^{ss} + f_2^s b_{21}^{ss} + f_1^r b_{11}^{rs} + f_2^r b_{21}^{rs}) y_1^s, \qquad (7)$$

It traces total emissions generated by the production of a final product in a particular country/industry according to where the needed intermediate inputs are produced along each stage (represented by different industries located in different countries) of the global production chain. This is the global "carbon footprint" of the consumption of sector 1's products from country *s*. The last two terms represent imported emissions.

In summary, the sum of the $\hat{F}B\hat{Y}$ matrix along a row represents the production-based emissions and shows how each country's emissions in a particular sector are distributed to final consumption (across columns) of all downstream countries/sectors (including itself), thus decomposes each country's total emissions by industry according to where the final consumption is made. It traces forward industrial linkages (downstream) from an emitter's perspective. The sum of the $\hat{F}B\hat{Y}$ matrix along a column accounts for all upstream countries/sectors' emissions to the production of a specific country/sector's final products (carbon footprint); it traces backward industrial linkages across upstream countries/industries (as different stages of production) from a user perspective, thus decomposes the total global emissions from the production of a country/sector's final goods and services according to where each of the needed intermediate inputs is produced.

As an example, in the chemical sector, the producer's perspective includes the emissions created by the production of chemicals that are embodied in the final goods exports of chemical products themselves (direct domestic emissions exports), as well as in the final exports of metal products, computers, consumer appliances, and machineries that use chemicals as inputs (indirect domestic emissions exports). Such a forward linkage perspective is consistent with the literature on the emissions content of trade. On the other hand, decomposition from a user perspective includes all upstream sectors/countries' contributions to emissions in a specific sector/country's final goods exports. For instance, in the automobile industry, it includes emissions generated in the automobile production itself as well as emissions embodied in inputs from all other upstream sectors/countries (such as rubber from country A, glass from country B, steel from country C, design and testing from the home country) used to produce an automobile for exports by the home country. Such a backward industrial-linkage-based perspective aligns well with case studies of emissions by a specific final product in the literature.

Each of these two different ways to decompose global total emissions has its own interpretations and thus different roles in environmental policy analysis. The decomposition of emissions by producing industry can address questions such as "who generates the emissions for whose consumption?" thus providing a starting point for the discussion of shared responsibility between producer and consumer at the industry level; while the decomposition of total emissions generated to produce a final product is able to answer questions such as "what is the global emissions level and what is the emission source (country/industry) structure required to produce a car in Germany compared to that for China?" and can attribute the total emissions for a final product to each stage of production in the global supply chain, thus providing facts that improve our understanding of the common but differentiated responsibilities among different production stages along each global supply chain.

With a clear understanding of how total national emissions by industry and total global emissions by the production of final goods and services at the country-sector level can be correctly estimated and decomposed by the standard Leontief method (equation (5) or the $\hat{F}B\hat{Y}$ matrix), we formally specify the decomposition methods used in this paper and their relations to other IO model based methods widely used in the literature.

2.2 Downstream decomposition: Decompose emissions generated from a country/industry based on forward industrial linkage

Extending equation (2) to a G country setting, the gross output production and use balance, or the row balance condition of a MRIO table becomes

$$X^s = A^{ss}X^s + \sum_{s\neq r}^{G} A^{sr}X^r + Y^{ss} + \sum_{s\neq r}^{G} Y^{sr} = A^{ss}X^s + Y^{ss} + \sum_{s\neq r}^{G} E^{sr} = A^{ss}X^s + Y^{ss} + E^{s*} \qquad (8)$$

where $E^{s*} = \sum_{s\neq r}^{G} E^{sr}$ is the total gross export of country s. Rearranging (8) gives

$$X^s = (I - A^{ss})^{-1}Y^{ss} + (I - A^{ss})^{-1}E^{s*} \qquad (9)$$

With a further decomposition of the gross exports into exports of intermediate/final products and their final destination of absorption, it can be shown that

$$\begin{aligned}(I - A^{ss})^{-1}E^{s*} &= (I - A^{ss})^{-1}\left(\sum_{r\neq s}^{G} Y^{sr} + \sum_{r\neq s}^{G} A^{sr}X^r\right) \\ &= \sum_{r\neq s}^{G} B^{sr}Y^{rs} + \sum_{r\neq s}^{G} B^{sr}A^{rs}(I - A^{ss})^{-1}Y^{ss} + \sum_{r\neq s}^{G} B^{ss}Y^{sr} + \sum_{r\neq s}^{G} B^{sr}Y^{rr} + \sum_{r\neq s}^{G} B^{sr}\sum_{t\neq s,r}^{G} Y^{rt}\end{aligned} \qquad (10)^{1}$$

Inserting (10) into (9) and pre-multiplying the direct emission intensity diagonal

---

[1] A detailed mathematical proof of equation (10) is provided in Appendix A.1.

matrix $\hat{F}$, we obtain an equation that decomposes total emissions by industry into different components.

$$P^s = \hat{F}^s X^s = \underset{(1)}{\hat{F}^s L^{ss}Y^{ss}} + \underset{(2)}{\hat{F}^s L^{ss}\sum_{r\neq s}^{G} A^{sr}\sum_{t}^{G} B^{rt}Y^{ts}} + \underset{(3)}{\hat{F}^s \sum_{r\neq s}^{G} B^{ss}Y^{sr}} + \underset{(4)}{\hat{F}^s \sum_{r\neq s}^{G} B^{sr}Y^{rr}} + \underset{(5)}{\hat{F}^s \sum_{r\neq s}^{G} B^{sr}\sum_{t\neq s,r}^{G} Y^{rt}}$$

(11)[1]

Here, $L^{ss} = (I - A^{ss})^{-1}$ is the local Leontief inverse.

There are five terms in equation (11), each of which represents emissions generated by the industry in its production to satisfy different segments of the global market. All the emissions that occur in region *s* are a result of various elements of production.

- The first term: domestically produced and consumed final goods and services ($L^{ss}Y^{ss}$).
- The second term: domestically produced intermediate goods exports ($L^{ss}A^{sr}\sum_{t}^{G} B^{rt}Y^{ts}$) which are used by other countries to produce either intermediate or final goods and services shipped back to the source country as imports and consumed there. [2]
- The third term: domestically produced final goods and service exports that are consumed by all of its trading partners ($B^{ss}Y^{sr}$).
- The fourth term: domestically produced intermediate goods and services exported to country *r* for the production of final products consumed in country *r* ($B^{sr}Y^{rr}$)

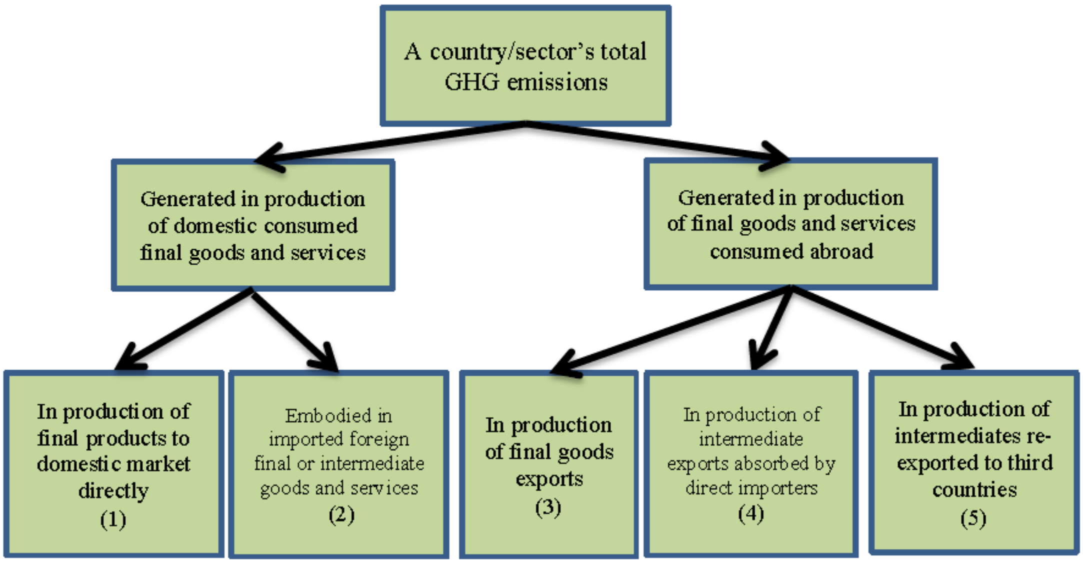
---

[1] The second term (2) on the right side in equation (11) equals to the sum of the first two terms on the right side in equation (10) (for detailed proof, see the appendix in Wang et al. 2013)

[2] his indicates the second term in (11) can be further split according to a country's final goods and intermediate goods imports and each particular trading partner that the imports come from.

- The fifth term: domestically produced intermediate goods exports to other countries producing their final goods and service exports to third countries $B^{sr}Y^{rt}$).

Figure 1 GHG emissions production, by sources of final demand – Forward industrial-linkage-based decomposition



Note the summation in the last three terms indicates that these emissions generated by export production can be further split into each trading partner's market. The sum of the last three terms gives the amount of emissions exports, and the sum of the last four terms in each bilateral route is the "Emissions Embodied in Bilateral Trade" (EEBT). Both measures are frequently used in the literature on embodied emissions in trade, which we will discuss in detail later in this paper. The disaggregated accounting for total emissions by industry based on forward industrial linkage (downstream decomposition) made by equation (11) is also diagrammed in Figure 1. The number in the lowest level box corresponds to the terms in equation (11).

2.3 Upstream decomposition: Decompose emissions from final goods and services by production stages in a global supply chain based on backward

industrial linkage

In the following we estimate the total emissions generated by a final product along the global supply chain identified by the last stage of production: a particular industry *i* located in a specific country *s*, which is denoted by y_i^s to be consistent in notation with the previous section. To produce y_i^s, activities x_j^s in industry $j = 1,\ldots, N$ at each country $s = 1,\ldots,G$ are needed[1]. We first need to know the levels of all gross outputs x_j^s associated with the production of y_i^s. This is estimated using the Leontief inverse as in equations (3) and (5).

To be more specific to our current analysis, let us extend equations (3) and (5) to cover any number of countries (*G*) and sectors (*N*). Then we obtain the following equations.

$$\begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^G \end{bmatrix} = \begin{bmatrix} B^{11} & B^{12} & \cdots & B^{1G} \\ B^{21} & B^{22} & \cdots & B^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ B^{G1} & B^{G2} & \cdots & B^{GG} \end{bmatrix} \begin{bmatrix} Y^1 \\ Y^2 \\ \vdots \\ Y^G \end{bmatrix} \tag{12}$$

$$\hat{F}_c B\hat{Y} = \begin{bmatrix} \hat{F}_c^1 & 0 & \cdots & 0 \\ 0 & \hat{F}_c^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \hat{F}_c^G \end{bmatrix} \begin{bmatrix} B^{11} & B^{12} & \cdots & B^{1G} \\ B^{21} & B^{22} & \cdots & B^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ B^{G1} & B^{G2} & \cdots & B^{GG} \end{bmatrix} \begin{bmatrix} \hat{Y}^1 & 0 & \cdots & 0 \\ 0 & \hat{Y}^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \hat{Y}^G \end{bmatrix}$$

---

[1] Production stages in the global supply chain are identified by each x_j^s, the maximum number of production stages of a specific supply chain in this accounting framework is *G by N*, assuming industries with the same classification but located in different countries produce differentiated products and so are located in different production stages of the global supply chain. Such an assumption is similar to the Armington assumption that has been widely used in CGE models for decades.

$$=\begin{bmatrix} \hat{F}_c^1 B^{11} \hat{Y}^1 & \hat{F}_c^1 B^{12} \hat{Y}^2 & \cdots & \hat{F}_c^1 B^{1G} \hat{Y}^G \\ \hat{F}_c^2 B^{21} \hat{Y}^1 & \hat{F}_c^2 B^{22} \hat{Y}^2 & \cdots & \hat{F}_c^2 B^{2G} \hat{Y}^G \\ \vdots & \vdots & \ddots & \vdots \\ \hat{F}_c^G B^{G1} \hat{Y}^1 & \hat{F}_c^G B^{G2} \hat{Y}^2 & \cdots & \hat{F}_c^G B^{GG} \hat{Y}^G \end{bmatrix} \tag{13}$$

With G countries and N sectors, A, B, $\hat{F}$ and $\hat{Y}$ are all $GN\times GN$ matrices. B^{sr} denotes the $N\times N$ block Leontief (global) inverse matrix, F_c^s is a 1 by N vector of direct emission intensities in country s, placed along the diagonal of the GN by GN matrix of $\hat{F}$. The subscript c represents type of energies and non-energies. Five types are considered: (1) coal, (2) petroleum, (3) gas, (4) waste, and (5) others (non-energy). $Y^s = \sum_r^G Y^{sr}$ is an $N\times 1$ vector that gives the global use of final goods produced by s. Each column of the $B\hat{Y}$ matrix of Equation (13) is a GN by 1 vector, the number of non-zero elements in such a column vector represents the number of production stages in our accounting framework for the global supply chain of a particular final good or service y_j^s.

Based on equation (13), we can decompose the total emissions of a final good or service by production stages and types of energy in a global supply chain based on backward industrial linkage as follows.

$$P_c(Y^s) = \hat{F}_c^s B^{ss} Y^s + \sum_{r\neq s}^G \hat{F}_c^r B^{rs} Y^s \; for\ c = 1,2,3,4,5 \tag{14}$$

$$P(Y^s) = \sum_{c=1}^5 P_c(Y^s) \tag{15}$$

The first term in equation (14) consists of the diagonal elements in the last matrix of equation (13), representing emissions generated in domestic production process;

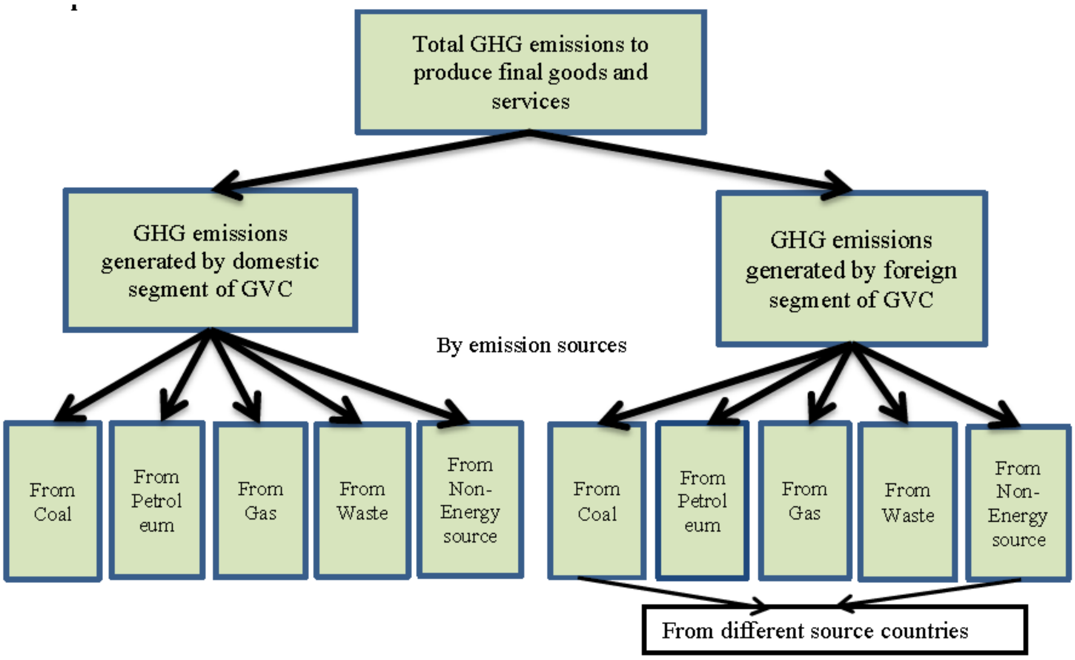
while the second term in equation (14) is the sum of off-diagonal elements across the row and in a column in the last matrix of equation (13), measuring emissions generated in foreign production processes. The summation in the second term indicates that these emissions generated by foreign production can be further split according to their source countries. Note that $\sum_{c=1}^{5} F_c^s = F^s$, that is, emission intensities by energy types in each country/industry sum to the total emission intensity of that country/industry. Therefore, equation (15) measures the total global emissions for the production of final products in country *s*. The decomposition of total emissions by the production of a final products in a global supply chain based on backward industrial linkage made by equations (14) is shown in Figure 2.

Based on equation (14), the consumption-based national emissions inventories for a particular product y_i^r can be estimated for each country as a sum weighted by consumption source structure:

$$P_c^{consumer}(y_i^{*r}) = \sum_{s}^{G} \frac{y_i^{sr}}{y_i^{*r}} P_c(y_i^{s*}) \quad \textit{for } c = 1,2,3,4\ 5\ ;\ i=1,2,\ldots N \qquad (16)$$

Here, $y_i^{s*} = \sum_{r}^{G} y_i^{sr}$ is the total final production in country *s* of product *i* for all countries, and $y_i^{*r} = \sum_{s}^{G} y_i^{sr}$ is the total final consumption in country *r* of product *i* sourced from all countries.

Figure 2 GHG emissions in global supply chains – backward ndustrial-linkage-based decomposition



Using the estimates from equation (14) and weighting by each country's source structure of the particular products it consumes, equation (16) allows one to estimate consumption-based emissions at country/product level and its results are different from emissions estimates obtained by using production emissions minus exported emissions plus imported emissions. Taking automobile as an example, the production plus net transfer method widely used in the literature only can provide estimates on how much of the emissions produced in the global auto industry is consumed in a country, which does not equal global emissions induced by the total automobile consumption in that country. However, summing over all products or industries, the total consumption-based emissions for a country will be the same regardless backward or forward linkage based computation is used.

2.4 Measures of embodied emissions in trade by various GVC routes and their role in linking production-based and consumption-based emissions accounts

In recent years, the international trade of embodied emissions has been a subject of substantial interest in both academic and policy circles. However, most MRIO-based measures of trade in embodied emissions in the literature have not made a clear distinction between emissions calculated by forward versus backward industrial linkages and often focus on the global and country aggregate level. As we will show in this section, such a distinction is not important at an aggregated level, but is crucial at a disaggregated level.

2.4.1 Forward industrial linkage based emission trade measures

At a bilateral sector or country sector level, emissions exports based on forward industrial linkages (we labeled as EEX_F) for sector *i* and region *s*, are the emissions generated in sector *i* to produce, directly and indirectly, gross exports from *s* to any other destination country except country *s* itself (e.g., emission exports from the US chemical sector would include emissions embodied in US steel and machinery sectors in addition to emission embodied in the US chemical sector). There are two key issues to highlight here. First, using the example of emissions exports from the US chemical industry, is that some of the emissions produced by that sector can be exported indirectly via other US sectors such as steel, because US produced chemicals are used as intermediate inputs in the production of steel exports. Second, the portion of the emissions that is associated with products first exported but eventually re-imported to satisfy domestic final demand is not part of the embodied emissions exports.

Emissions embodied in a country’s gross exports, which we labeled as EEG, refer to emissions generated from the production of the country’s gross exports. Because this measure focuses only on where the emissions come from but not where they are absorbed, it does not exclude the part of the emissions that is generated by producing intermediate inputs for other countries but eventually returns home via imports (i.e., is re-imported) to satisfy domestic final demand. It is conceptually similar to emissions embodied in bilateral trade (EEBT) defined by Peters (2008) and Peters et al. (2011). The EEG based on forward industry linkage, EEG_F, refers to the part of emissions generated from the production of the country’s gross exports from all sectors that originated from a particular domestic sector, including the portion that eventually returns (which will be labeled REE_F) via imports. Because we already have a complete decomposition of emissions by industry in equation (11), it is convenient to mathematically specify EEX_F, emissions generated in production to satisfy foreign final demand, and REE_F, emissions generated in the production of intermediate exports for other countries which are then used to produce their exports and shipped back to country *s* as follows.

$$EEX\_F^{sr} = \hat{F}^{s} B^{ss} Y^{sr} + \hat{F}^{s} B^{sr} Y^{rr} + \hat{F}^{s} \sum_{t \neq s,r}^{G} B^{st} Y^{tr} \tag{17}$$

$$REE\_F^{sr} = \hat{F}^{s} L^{ss} A^{sr} \sum_{t}^{G} B^{rt} Y^{ts} = \hat{F}^{s} L^{ss} A^{sr} B^{rr} Y^{rs} + \hat{F}^{s} L^{ss} A^{sr} \sum_{t \neq s,r}^{G} B^{rt} Y^{ts} + \hat{F}^{s} L^{ss} A^{sr} B^{rs} Y^{ss} \tag{18}$$

Equation (17) is the sum of the third and fourth terms in equation (11) plus an additional term taken from the last term of equation (11) which only sums over third country *t* re-exports to a particular trading partner *r* (without the second summation over all *r*). Equation (18) is a further decomposition of the second term in equation (11). It measures domestic emissions embodied in intermediate exports from country *s* to country *r* that return to *s* and are ultimately absorbed in *s* via all possible routes through forward industrial linkage. Both portions are emissions related to international trade but for different market segments.

We specify domestic emissions embodied in gross exports from country *s* to country *r* based on forward industrial linkages as

$$\begin{aligned} EEG\_F^{sr} = \hat{F}^{s} L^{ss} E^{sr} &= \underbrace{\hat{F}^{s} L^{ss} Y^{sr}}_{(1)} + \underbrace{\hat{F}^{s} L^{ss} A^{sr} \sum_{t}^{G} B^{rt} Y^{tr}}_{(2a)} \\ &+ \underbrace{\hat{F}^{s} L^{ss} A^{sr} \sum_{t}^{G} B^{rt} Y^{ts}}_{(2b)} + \underbrace{\hat{F}^{s} L^{ss} \left[A^{sr} \sum_{r \neq s}^{G} B^{rt} Y^{tt} + A^{sr} \sum_{t \neq s,r}^{G} B^{rs} Y^{st} \right]}_{(2c)} \end{aligned} \qquad (19)$$

It measures what amount of domestic emissions can be generated from the production of gross exports E^{sr} in country *s*, regardless whether these gross exports are finally absorbed in importing country *r* or not. It can be decomposed into two parts:

1. Domestic emissions generated from the production of final goods exports,
2. Domestic emissions generated from the production of intermediate goods exports that are:

2a. finally absorbed in the direct importing country *r*,

2b. returned (re-imported) to the exporting country *s*, or

2c. re-exported to a third country *t*.

It is identical to the "Emissions Embodied in Bilateral Trade" (EEBT) defined by others (Peters 2008; Peters and Hertwich 2008) in the literature on embodied emissions in trade. It is easy to see that REE_F^{sr} defined by equation (18) is exactly the third term in equation (19). We can show that, at the bilateral-sector level, $\hat{F}^{s} L^{ss} E^{sr} \neq (EEX\_F^{sr} + REE\_F^{sr})$ due to indirect emissions exports through third countries. However, after aggregating over all trading partners, at the country-sector level,

$$\sum_{r \neq s}^{G} EEG\_F^{sr} = \sum_{r \neq s}^{G} (REE\_F^{sr} + EEX\_F^{sr}) = \sum_{r \neq s}^{G} \hat{F}^{s} L^{ss} E^{sr} \tag{20}$$

The step by step derivation of equations (18) to (20) can be found in appendix A.2. The intuition behind the derivation is simple: both EEX_F^{sr} and REE_F^{sr} require that the emissions associated with a product is consumed in destination country *r* by definition, while EEG_F^{sr} or EEBT do not have such restrictions and are concerned only where these emissions are generated, regardless of where their associated products are finally absorbed.

Similar to Peters et al. (2011), we define the balance of embodied emissions in trade, or “net emissions transfer” as

$$T^{s} = \sum_{r \neq s}^{G} EEX\_F^{sr} - \sum_{s \neq r}^{G} EEX\_F^{rs} \tag{21}$$

It is easy to show that T^{s} equals the difference between production-based and consumption-based emission inventory. That is,

$$T^{r} = P^{producerer}(y_i^{r}) - P^{consumer}(y_i^{r}) \,. \tag{22}$$

2.4.2 Backward industrial linkage based emission trade measures

Embodied emissions exports calculated by backward industrial linkages at a bilateral sector or country-sector level, which we labeled as EEX_B, refer to the amount of emissions generated by the production of a particular sector's gross exports (e.g., US auto), which will include emissions produced by any domestic sectors (e.g., including US rubber, chemicals, steel, and glass) via backward industrial linkages, and is ultimately absorbed abroad or in a particular destination country. There are also two key features to take into account. First, the measure quantifies emissions to the sector whose products are exported. Second, the concept excludes the part of domestic emissions that is eventually re-imported. In general, at the country sector and bilateral sector level, EEX_F and EEX_B are not the same except by coincidence. However, once we aggregate across all sectors, the distinction between EEX_F and EEX_B disappears.

To trace emissions generated by gross trade flows at bilateral and sector levels, it is useful to think of the total domestic emissions associated with gross trade flows that is absorbed abroad, denoted by EEX, as a distinct concept from EEX_B or EEX_F in order to measure emissions embodied in a particular bilateral gross trade flows. It is also based on backward industrial linkages and is also ultimately absorbed abroad, similar to EEX_B, but does not require domestically produced emissions to be absorbed in a particular destination country. In other words, at the country sector level, this third trade-in-emissions measure is the same as EEX_B, but at the bilateral or bilateral sector level, they are different. As we will show later in this paper, EEX is the only emissions trade measure that is consistently associated with bilateral gross trade flows, while both EEX_F and EEX_B are not, due to indirect emissions trading through third countries. All these three measures exclude the part of domestic emission that first exported but eventually returns home. However, all of them are useful to trace emission trade in gross exports for different purpose beyond the country aggregate level. For instance, if one wishes to understand the global emissions level generated by a country's gross exports and its source structure, the backward-linkage-based emissions measures are the right one to use. If one wishes to understand the responsibility for emissions from a given sector in the country's gross exports from all sectors, one should use the forward-linkage-based measures.

As we have already shown, to decompose a country/industry's total GHG emissions by source of final demand and measure domestically produced emissions embodied in a country's gross exports from all sectors based on forward industrial linkage, applying Leontief's original method is sufficient. However, for measuring global emissions generated by a country's gross exports and tracing its source structure based on backward industrial linkage, Leontief's original method will not be sufficient, as it does not provide a way to decompose gross intermediate trade flows across countries according to their final absorption, as illustrated by Wang et al. (2013) in their recent work.

Following Wang et al.'s innovative intermediate trade flow decomposition method, we define our bilateral emissions trade measures based on backward industrial linkage as

$$\begin{aligned} EEX^{sr} &= (F^s B^{ss})^T \# Y^{sr} + (F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rr}) \\ &+ (F^s L^{ss})^T \# \left\{ (A^{sr} B^{rr} \sum_{t\neq s,r}^{G} Y^{rt}) + (A^{sr} \sum_{t\neq s,r}^{G} B^{rt} Y^{tt}) + (A^{sr} \sum_{t\neq s,r}^{G} \sum_{u\neq s,t}^{G} B^{rt} Y^{tu}) \right\} \end{aligned} \tag{23}$$

$$\begin{aligned} EEX\_B^{sr} &= (F^s B^{ss})^T \# Y^{sr} + (F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rr}) \\ &+ (F^s L^{ss})^T \# \left\{ (\sum_{t\neq s,r}^{G} A^{st} B^{tt} Y^{tr}) + (A^{sr} \sum_{t\neq s,r}^{G} B^{rt} Y^{tr}) + (\sum_{t\neq s,r}^{G} \sum_{u\neq s,t}^{G} A^{st} B^{tu} Y^{ur}) \right\} \end{aligned} \tag{24}$$

where “#” is an element-wise matrix multiplication operator[1]. To facilitate the understanding of the three terms in the emissions trade measure defined in equation (23), we provide the following intuitive interpretations.

The the 1st term, $(F^s B^{ss})^T \# Y^{sr}$, represents domestic emissions generated by the production of final exports from country *s* to country *r*. The 2nd term, $(F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rr})$, represents domestic emissions generated by the production of intermediate exports from country *s* used by direct importer (country *r*) to produce final goods and services which are consumed in country *r*. The 3rd term, $(F^s L^{ss})^T \# \{\ldots\}$ represents domestic emissions generated by the production of intermediate exports from country *s* used by the direct importer (country *r*) to produce intermediate or final goods and services that are re-exported to a third country *t*. The three elements in the parenthesis, $A^{sr} B^{rr} \sum_{t\neq s,r}^{G} Y^{rt}$, $A^{sr} \sum_{t\neq s,r}^{G} B^{rt} Y^{tt}$, and $A^{sr} \sum_{t\neq s,r}^{G} \sum_{u\neq s,t}^{G} B^{rt} Y^{tu}$ show how the re-exports are produced in country *r* by using intermediate exports from country *s* as inputs. They represent final goods re-exports, intermediate goods re-exports for third countries’ domestically consumed final goods, and intermediate goods re-exports for third countries’ final goods exports, respectively.

---

[1] For example, when a matrix is multiplied by $n \times 1$ column vector, each row of the matrix is multiplied by the corresponding row element of the vector.

It is interesting to note that the difference between EEX^{sr} (23) and EEX_B^{sr} (24) appears in only the third country term (the third term). The former includes emissions absorbed not only by country *r*, but also by third countries *t* and *u* (last three terms in equation 24). The latter includes not only emissions exports from country *s* embodied in its own gross exports to country *r* (the 1st and 2nd terms in equation 24, which are the same as the first two terms in equation 23), but also emissions exports by country *s* embodied in its gross exports to third country *t*, that are finally absorbed by country *r* (the last terms in equation 24). This illustrates why we claim that EEX^{sr} is the only measure of emission trade which is consistently associated with bilateral gross trade flows. Both emissions export measures are deviate from gross bilateral trade flows due to indirect trade through third countries.

Similar to the definition of EEG_F, we could also define EEG_B, the measure of domestic emissions generated from the production of bilateral gross exports at sector level based on backward industrial linkage, which refers to emissions from all domestic sectors induced by the production of a particular sector's gross exports to a particular trading partner or the rest of the world, including the portion of emissions associated with exported products that are eventually re-imported, REE_B.

$$\begin{aligned} EEG\_B^{sr} &= (F^s L^{ss})^T \# E^{sr} = (F^s L^{ss})^T \# Y^{sr} + (F^s L^{ss})^T \# A^{sr} \sum_{t}^{G} B^{rt} Y^{tr} \\ &+ (F^s L^{ss})^T \# A^{sr} \sum_{t}^{G} B^{rt} Y^{ts} + (F^s L^{ss})^T \# \left[A^{sr} \sum_{r \neq s}^{G} B^{rt} Y^{tt} + A^{sr} \sum_{t \neq s,r}^{G} B^{rs} Y^{st} \right] \end{aligned} \qquad (25)$$

EEG_B^{sr} measures what amount of domestic emissions can be generated from all sectors in country *s* in the production of gross exports E^{sr}, regardless of whether these exports are finally absorbed in importing country *r* or not. The four terms in equation

(25) have similar interpretations to those of the four terms in equation (20); the differences are that these terms include not only domestic emissions generated by the exporting sectors, but also those of other upstream domestic sectors that contribute to the production of a particular sector's gross exports.

We define emissions embodied in intermediate exports that are first exported but ultimately returned and absorbed at home based on backward industrial linkages from country *s* to country *r* as:

$$\begin{aligned} REE\_B^{sr} &= (F^s L^{ss})^T \# A^{sr} \sum_{t}^{G} B^{rt} Y^{ts} \\ &= (F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rs}) + (F^s L^{ss})^T \# (A^{sr} \sum_{t \neq s,r}^{G} B^{rt} Y^{ts}) + (F^s L^{ss})^T \# (A^{sr} B^{rs} Y^{ss}) \end{aligned} \tag{26}$$

It can be seen that *REE_B*^{sr} is exactly the third term in equation (25). We can show that *EEG_B*^{sr} equals the sum of equations (23) and (26) at the country aggregate level only.

$$\sum_{r \neq s}^{G} uEEG\_B^{sr} = \sum_{r \neq s}^{G} u(EEX^{sr} + REE\_B^{sr}) = \sum_{r \neq s}^{G} F^s L^{ss} E^{sr} \tag{27}$$

where, *u* is a 1 by *N* unit vector. Detailed proofs of equations (25) to (27) are given in appendix A.3.

To completely measure total emissions from the production of a country's gross exports, emissions generated in other countries that provide intermediate inputs for the exporting country also have to be estimated. The foreign-produced emissions embodied in a country's gross exports (FEE) can be defined as

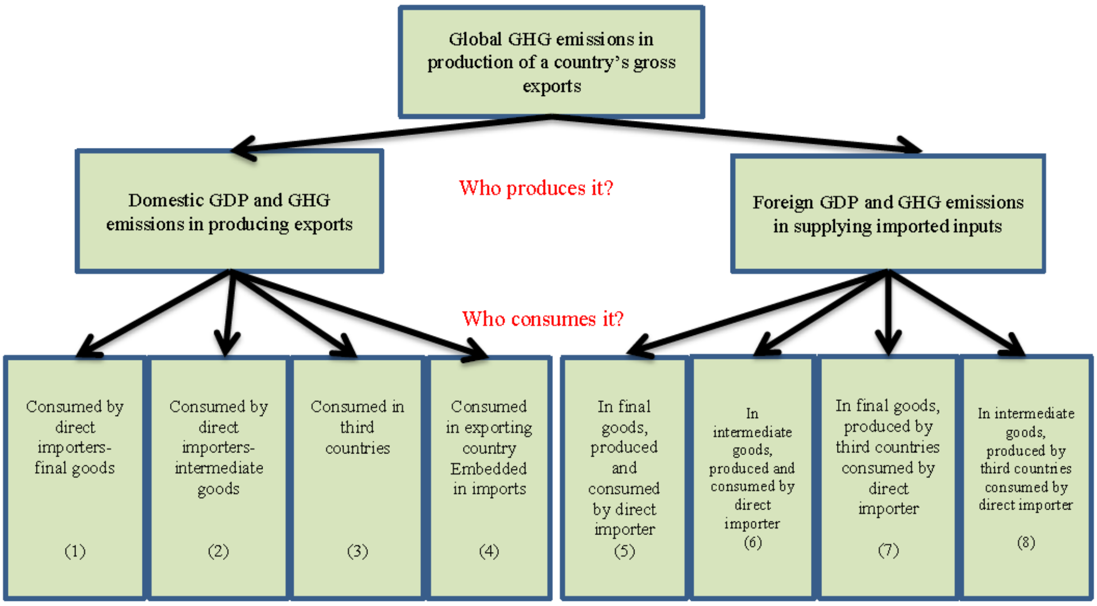
$$\begin{aligned} FEE^{sr} &= (F^r B^{rs})^T \# Y^{sr} + (F^r B^{rs})^T \# (A^{sr} L^{rr} Y^{rr}) \\ &+ (\sum_{t \neq s,r}^{G} F^t B^{ts})^T \# Y^{sr} + (\sum_{t \neq s,r}^{G} F^t B^{ts})^T \# (A^{sr} L^{rr} Y^{rr}) \end{aligned} \tag{28}$$

Each term in equation (28) has an intuitive interpretation. The first term, $(F^r B^{rs})^T \# Y^{sr}$, is the importer's (country *r*) emissions embodied in the final exports of country *s* to country *r*. The second term, $(F^r B^{rs})^T \# (A^{sr} L^{rr} Y^{rr})$, is the importer's emissions embodied in the intermediate exports of country *s* to country *r*, which are then used by country *r* to produce its domestic final goods and services. The third term, $(\sum_{t \neq s,r}^{G} F^t B^{ts})^T \# Y^{sr}$, is foreign emissions from third countries *t* embodied in the final exports of country *s* to country *r*. The last term, $(\sum_{t \neq s,r}^{G} F^t B^{ts})^T \# (A^{sr} L^{rr} Y^{rr})$, is foreign emissions from third country *t* embodied in the intermediate exports of country *s* to country *r*, which are then used by country *r* as inputs to produce its domestic final goods and services.

Combining equations (23), (26) and (28), we decompose the total global emissions generated from the production of a country's gross exports to its trading partner as

$$
\begin{aligned}
P(E^{sr}) = & \underset{(1)}{(F^s B^{ss})^T \# Y^{sr}} + \underset{(2)}{(F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rr})} \\
& + \underset{(3)}{(F^s L^{ss})^T \# \left\{ (A^{sr} B^{rr} \sum_{t \neq s,r}^{G} Y^{rt}) + (A^{sr} \sum_{t \neq s,r}^{G} B^{rt} Y^{tt}) + (A^{sr} \sum_{t \neq s,r}^{G} \sum_{u \neq s,t}^{G} B^{rt} Y^{tu}) \right\}} + \underset{(4)}{(F^s L^{ss})^T \# A^{sr} \sum_{t}^{G} B^{rt} Y^{ts}} \qquad (29) \\
& + \underset{(5)}{(F^r B^{rs})^T \# Y^{sr}} + \underset{(6)}{(F^r B^{rs})^T \# (A^{sr} L^{rr} Y^{rr})} + \underset{(7)}{(\sum_{t \neq s,r}^{G} F^t B^{ts})^T \# Y^{sr}} + \underset{(8)}{(\sum_{t \neq s,r}^{G} F^t B^{ts})^T \# (A^{sr} L^{rr} Y^{rr})}
\end{aligned}
$$

Figure 3 Decomposition of global GHG emissions in the production of gross exports by different GVC routes – based on backward industrial-linkage



The first four terms of equation (29) represent emissions within the exporting country, which are a by-product of generating the exporting country's GDP; the last four terms in equation (29) represent emissions within foreign countries that provide intermediate inputs for the exporting country, but also create GDP for these foreign countries. The decomposition made in equation (29) is also shown in Figure 3.The number in the lowest level box corresponds to the terms in equation (29).

2.4.3 Relationships among different emissions trade measures

It turns out that separating emissions by backward versus forward industrial linkages is crucial to properly tracing emissions in trade at a disaggregated level. To our knowledge, the literature on embodied emissions in trade has not previously made a clear distinction between them. While Peters et al. (2011) made a distinction between emissions embedded in bilateral trade (EEBT) versus embodied emissions of final consumption, they do so only at the country aggregate level. More importantly, they do not distinguish backward from forward industrial linkages—such a distinction is not important at the country aggregate level, but is crucial at a disaggregated level. Therefore, a key contribution of this paper is to systematically develop these quantitative emissions trade measures at both aggregated and disaggregated levels. The relationships among these different emissions trade measures can be summarized as follows:

In a world of three or more countries, domestic emissions generated by the production of bilateral gross exports to satisfy foreign final demand (EEX), forward linkage-based emissions exports (EEX_F), and backward linkage-based emissions exports (EEX_B) are, in general, not equal to each other at the bilateral/sector level, though they are the same at the country aggregate level. EEX_F and EEX_B are also equal at the bilateral aggregate level, while EEX and EEX_B are the same at the country/sector level.

EEG_F and (EEX_F + REE_F) are equal to each other at both country sector and country aggregate levels, but not equal at the bilateral sector level; while EEG_B and (EEX_B+ REE_B) are equal to each other only at the country aggregate level. Because both REE_F and REE_B are non-negative, EEG_F is always greater than or equal to EEX_F at country/sector level; both EEG_F and EEG_B are always greater than or equal to all the three measures of trade in embodied emissions (EEX, EEX_F and EEX_B) at the country aggregate level. While at the bilateral sector level, EEG (EEBT) measures can greater or smaller than EEX measures, as discussed in detail by Peters (2008). Finally, EEX_F and EEG_F as well as (EEX_F+REE_F) are always less than or equal to the sector-level total emission production $P(y_i^s)$.

The intuition behind these statements is simple: since direct emissions exports at the sector level are the same for all three trade-in-emissions measures, only indirect emissions trades may differ. However, because such indirect emissions exports are part of the total emissions produced by each sector, the total emissions in a country/sector set an upper bound for forward linkage-based emissions exports and domestic emissions embedded in gross exports.

The definition of all the embodied emission trade measures discussed in this section and their relationships are summarized in Tables 1a and 1b below:

Table 1a Definition of different measures of embodied emissions in trade

Acronym or label	Definition in words	Key characters	Equation # in text
EEX_F	Embodied emissions exports, forward-linkage-based	1. Emissions generated in producing goods and services that satisfy foreign final demand; 2. Include indirect emissions exports ; 3. Excluding emissions associate with intermediate exports that are returned and absorbed at home 4. Trade concepts, produced in one country, consumed by another.	**17**
EEX_B	Embodied emissions exports, backward linkage –based		**24**
EEX	Embodied emissions associated to gross bilateral trade flows		**23**
REE_F	Embodied emissions return home, forward linkage–based	Emissions generated by producing intermediate inputs exported to other countries, which eventually returns home via imports to satisfy domestic final demand	**18**
REE_B	Embodied emissions return home, backward linkage–based		**26**
EEG_F	Emissions embodied in a country's gross exports, forward linkage-based	1. Production concept, consistent to GDP by industry statistics 2. Focuses only on where the emissions are produced 3. Include the part of emissions that is generated by producing intermediate inputs for other countries but eventually re-imported	**19**
EEG_B	Emissions embodied in a country's gross exports, backward-linkage-based		**25**

Table 1b Relationships among different measures of embodied emissions in trade

	Aggregation level	EEX & EEX_F	EEX & EEX_B	EEX_F & EEX_B	REE_F & REE_B	EEG_F & EEG_B	EEG_F & (EEX_F+ REE_F)	EEG_B & (EEX_B+ REE_B)
e_i^{sr}	Bilateral-Sector	$\neq$	$\neq$	$\neq$	$\neq$	$\neq$	$\neq$	$\neq$
$\sum_{i=1}^{N} e_i^{sr}$	Bilateral Aggregate	$\neq$	$\neq$	$=$	$=$	$=$	$\neq$	$\neq$
$\sum_{r \neq s}^{G} e_i^{sr}$	Country-Sector	$\neq$	$=$	$\neq$	$\neq$	$\neq$	$=$	$\neq$
$\sum_{r \neq s}^{G} \sum_{i=1}^{N} e_i^{sr}$	Country Aggregate	$=$	$=$	$=$	$=$	$=$	$=$	$=$

3. Empirical analysis

Following the concepts and accounting framework proposed above, this section uses the WIOD[1] to demonstrate how this framework can help to gain a deeper understanding of the relationships between GVCs and CO_2 emissions from different perspectives. While we focus on CO_2 here, the framework works in the same way for any environmental stressor.

3.1 Tracing CO_2 emissions in GVCs at the national level

We first apply the accounting framework at the national level to demonstrate the concepts summarized in Figures 1, 2, and 3.

Figure 4 shows “who produced CO_2 emissions for whom” by different GVC routes in 2009, using the two largest emitters, China and the US, as an example. This figure follows the forward industrial-linkage-based downstream decomposition method

---

[1] www.wiod.org

(Figure 1). Clearly, most CO_2 emissions (EH_F) are the result of satisfying the domestic final demand in each country that not relate to international trade. This result holds for most large economies since the self-sufficient portion normally accounts for the largest part of total final demand. However, compared to the US, this portion is much lower in China. More than 30% of China's CO_2 emissions are induced by foreign final demand (EEX_F=EEX_F1+EEX_F2+EEX_F3). This is mainly for two reasons: 1) after China's accession to the WTO, foreign final demand has played an increasing role in driving the growth of China's GDP and the generation of China's CO_2 emissions (Peters et al. 2011); 2) the CO_2 emission intensity for producing one unit GDP in China is higher than that in the US (Davis and Caldiera 2010) (also see Appendix B4).

As we discussed in section 2, part of the CO_2 emissions induced by domestic final demand depend on international trade due to production sharing between home and foreign countries, measured by REE_F. As an example, producing a car in China to satisfy China's own final demand may require the importation of an engine from the US, which may use Chinese metal parts as inputs in its production. As a result, China's final demand for its domestic final products may cause its own CO_2 emissions to rise through the two-way international trade in intermediate goods and services. The forward industrial-linkage-based downstream decomposition method can also be used to trace foreign final demand in driving home-country produced CO_2 emissions by different GVC routes. As also shown in Figure 4, the share of CO_2 emissions induced by foreign final demand through final goods trade (EEX_F1) for China is obviously larger than that for the US. This depends on both the CO_2 emission intensity and how a country participates in GVCs. Most developing countries, such as China, join GVCs through exporting relatively large amounts of final products in their early stage of development.

Figure 4 Who produces emissions for whom (forward industrial-linkage-based decomposition, 2009)

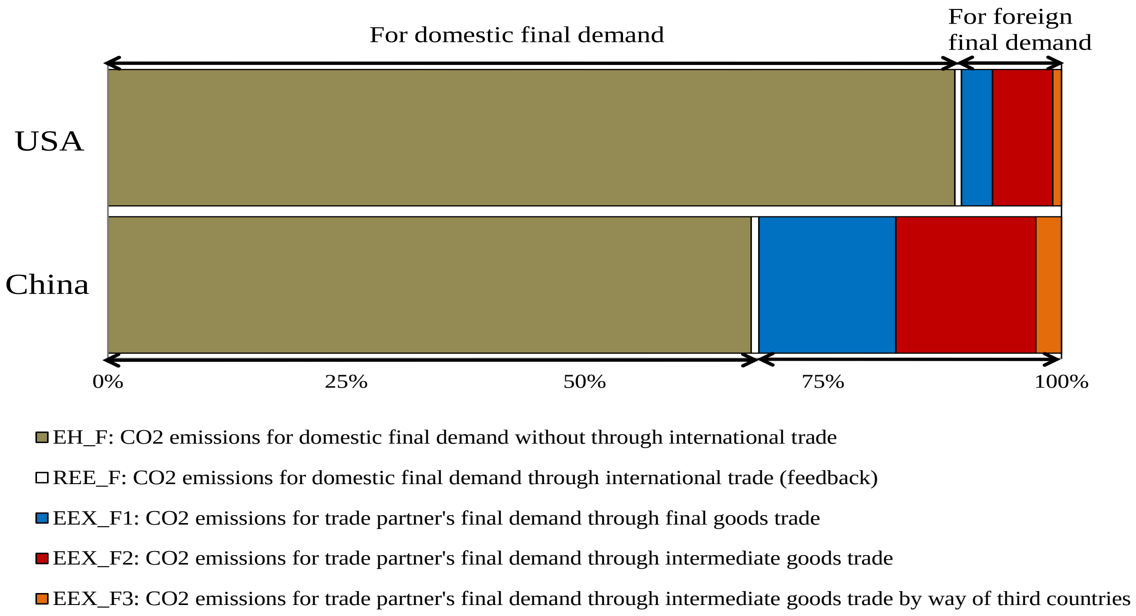


Figure 5 uses Germany and China as an example to show how CO_2 emissions are generated from upstream production stages in GVCs by different emission sources when these two countries produce final goods and services. This figure follows the backward industrial-linkage-based upstream decomposition method (Figure 2). The foreign emissions induced by the production of final goods and services in Germany account for a relatively large share (more than 35% in 2009) compared to that in China (less than 10% in 2009). This depends not only on all related countries' CO_2 emission intensities, but also their cross country production sharing arrangements and the way they participate in GVCs. China's CO_2 emission intensity is higher than that of Germany (see Appendix B4); this makes China's domestic emissions take a relatively large share in the production of final goods. On the other hand, Germany's value chain has a relatively large foreign segment (relative to China, a country which is less integrated into the European Union), so more emissions may occur in other countries due to the induced demand for intermediate imports used for producing German-made final products.

In addition to technological efficiency, the amount of induced CO_2 emissions when producing final products may also depend on the structure of energy use in upstream production processes. For example, the usage of coal accounts for a very large portion of domestic emissions for China and relatively large portion of foreign emissions for Germany when producing final goods and services. In general, this indicator can help us clearly understand how a country's production of final goods and services impact on the CO_2 emissions in its upstream countries or industries (domestic or foreign) through various GVC routes.

Figure 5 Induced emissions in both domestic and international segments of GVC when a country produces final goods and services (backward industrial-linkage-based decomposition, 2009)

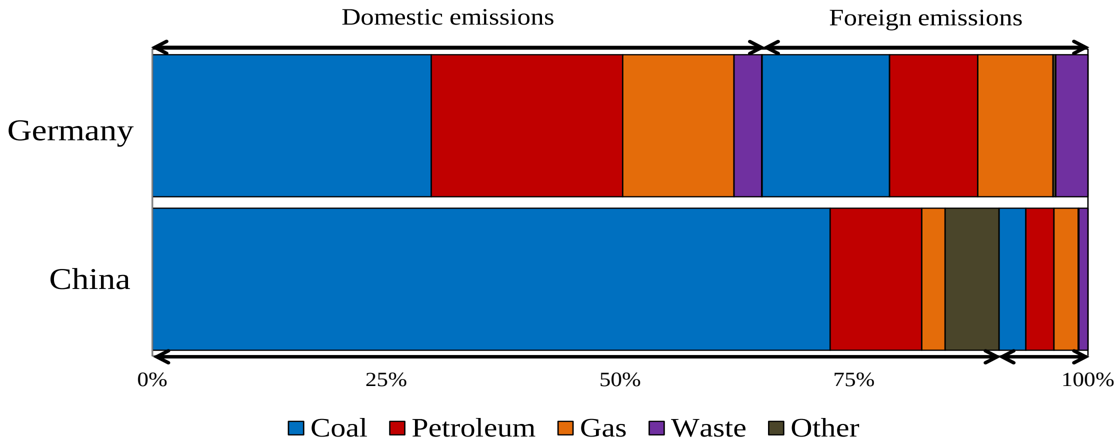
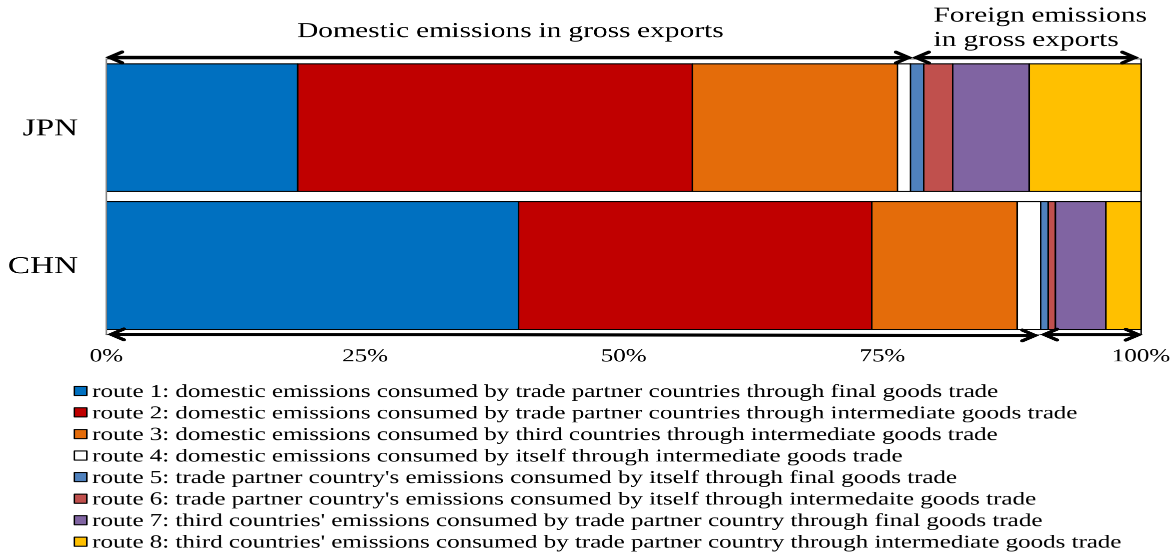


Figure 6 shows how Japan and China’s gross exports generate both domestic and foreign CO_2 emissions by different GVC routes in 2009 (cf. Davis and Caldiera 2010). This figure corresponds to the backward industrial-linkage-based decomposition of gross exports (Figure 3). Compared to Japan, domestic CO_2 emissions generated from China’s gross exports production account for a relatively large share (more than 90%). Though China imports more intermediate inputs than Japan does in producing gross exports, lower energy efficiency and high carbon intensity are the main drivers that increase China’s domestic emissions share in gross exports. When looking at the domestic CO_2 emissions by GVC routes, a remarkable difference between Japan and China can be observed: Japan’s domestic CO_2 emissions in gross exports are mainly generated in the production of intermediate goods and services that are exported to its trading partners, while, for China, final goods exports play a dominant role. This depends on both the way a country participates in GVCs and its CO_2 emission intensity. As a result of its comparative advantage in assembly, exports final products is one of the major ways that China participates in GVCs. While Japan participates in GVCs largely through high-tech intermediate exports as a result of its comparative advantage in capital and skill intensive activities. Though the major exports with high comparative advantage for China are textile and electrical products which may not emit a large amount of CO_2 in their production processes, domestic intermediate inputs such as high-carbon electricity and chemicals are directly and indirectly embodied in these final product exports. As a result, domestic CO_2 emissions through final goods trade in China accounts for a relatively large share of its total emissions induced by gross exports.

Figure 6 Emissions embodied in gross exports by eight GVC routes (backward industrial-linkage-based decomposition, 2009)



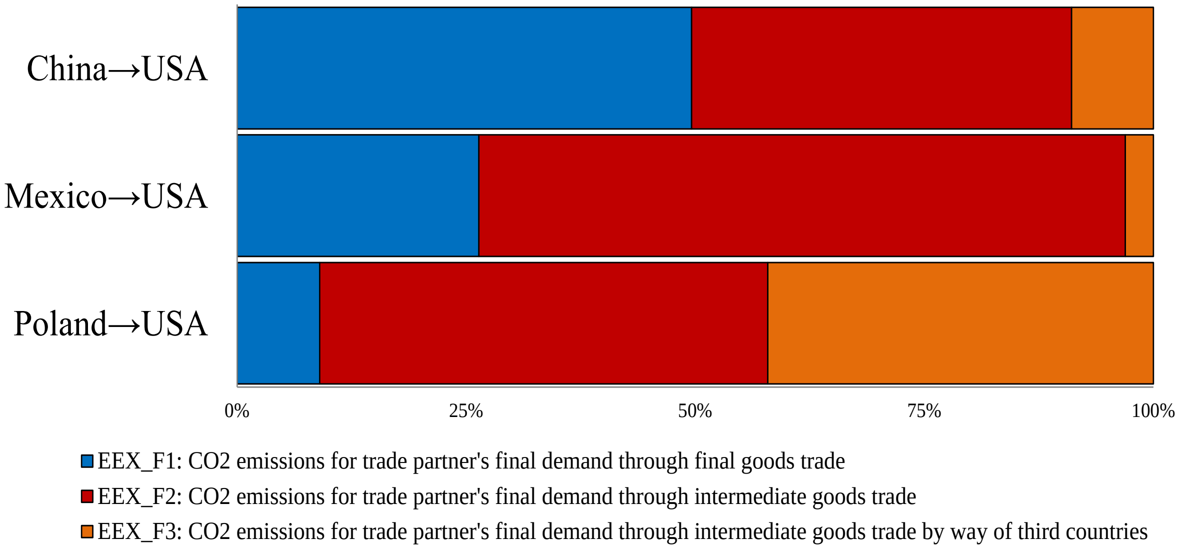
The share of foreign CO_2 emissions in a country's gross exports also depends on its trading partners' CO_2 emission intensities. Japan's import content in exports is lower than that of China, but its foreign emissions in gross exports are higher. This implies that relatively high foreign carbon intensity goods are embodied in Japan's gross exports. In addition, one important advantage of using this framework is that we can easily understand who produces gross exports and CO_2 emissions for whose consumption through which specific GVC route. For example, about 20% of CO_2 emissions in Japan's gross exports is for satisfying its direct trading partner's final demand, but this is emitted in third countries through Japan's use of third countries' intermediate goods and services to produce its exports to the partner country (route 7 and 8). Given the rapid extension of international fragmentation of production, this type of emissions in international trade tends to increase if no global treaty is in place. We report more detailed results on CO_2 emissions based on the 3 type decomposition method discussed in section 2 at the national level for the years between 1995 and 2009 in Appendix B1- B3.

3.2 Tracing CO_2 emissions in GVCs at the bilateral and sectoral levels

As discussed in section 2, the unified accounting framework proposed in this paper can also be used to trace CO_2 emissions in GVCs at detailed bilateral and sectoral levels. Figure 7 shows how emissions are generated in the CO_2 intensive metal industry in three selected countries, China, Mexico, and Poland, to satisfy US final demand through different GVC routes. This figure corresponds to Figure 1 following the forward industrial-linkage-based decomposition method. We use these three countries as an example here because they are all active players in GVCs of metal products and are also important direct or indirect trading partners of the US, while being located in three different continents: North America, Asia, and Europe. In addition, for most countries, the metal industry is always one of the largest emitters, with relatively high carbon intensity.

Figure 7 shows the CO_2 emissions in the metal industries in these three countries from activities to satisfy US's final demand via different GVC routes. The pattern is mainly determined by a country's position and participation in GVCs. China exports large quantities of final products to the US, so we see China's metal industry's CO_2 emissions from satisfying US's final demand arising mainly through final goods trade. Mexico is also close to the US consumer but unlike China, it is located in a relative upstream position in metal GVCs: it is one of the largest providers of parts and components of metal products to the US, for example, for the US auto industry. As a result, the CO_2 emissions in Mexico's metal industry are mainly embodied in its export of intermediate goods which are directly and indirectly consumed in the US. Poland is much further from the US consumers and is embedded in the EU economy, so it is located far upstream in the GVCs of metal products. Therefore, a large portion of Poland's metal industry CO_2 emissions are embodied in goods traded with third countries, such as metal products used in a German car finally consumed in the US. Tracing CO_2 emissions at the bilateral and sector levels as this example can help us to better understand the effect of a country's position and participation in GVC on the geographic source of its CO_2 emissions at the industry level.

Figure 7 Metal industry's CO2 emissions exports from selected countries to the US by different GVC routes (forward industrial-linkage-based decomposition, 2009)

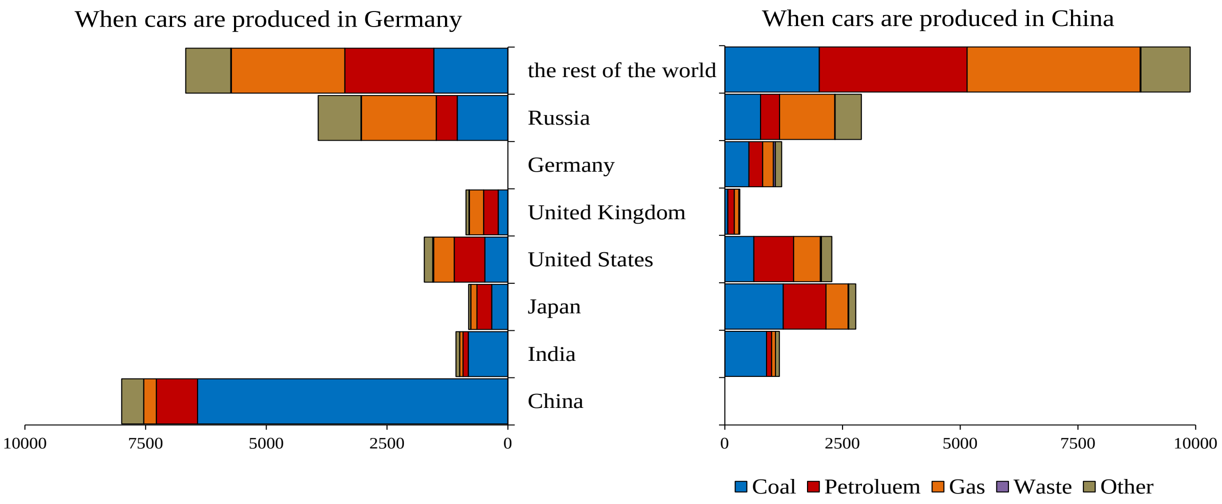


Following the accounting method summarized in Figure 2, we use German-made and Chinese-made cars as an example to demonstrate how these two large car producers cause upstream country's CO_2 emissions in automobile GVCs. Figure 8 shows China, the rest of the world (RoW), and Russia are the economies most affected by car production in Germany, besides Germany itself. On the one hand, this is because these three economies are located upstream of Germany's car value chain through providing intermediate goods and services directly or indirectly for German car production. On the other hand, it is a result of the relatively high carbon intensity for producing intermediate goods in these countries compared to other upstream countries, like the US and Japan. Another important factor is that different upstream countries involved in Germany's car value chain rely on different energy sources to produce their intermediate exports. For instance, China mainly relies on coal-based energy, hence coal-based CO_2 emissions account for the majority of emissions in China resulting from car production in Germany. This also implies that emissions to produce German cars will decrease substantially if China can replace coal by other green energy sources in producing intermediate goods purchased by the Germans. Compared to the German-made car, the production activities of auto makers in China have a larger impact on CO_2 emissions in the RoW and Russia. China overtook the US, becoming the world's top auto maker and market in 2009[1]. Large amounts of components are imported from the RoW through various GVC routes directly and indirectly. As a result, the RoW has been the most affected upstream region in the production of Chinese-made cars. In addition, Japan and the US are also heavily affected since both countries are located in the upstream of China's car value chain by providing high-tech intermediate goods and services. This is different from the cars made in Germany because Germany may obtains almost all high-tech parts from its domestic suppliers rather than its main rivals, the US and Japan.

---

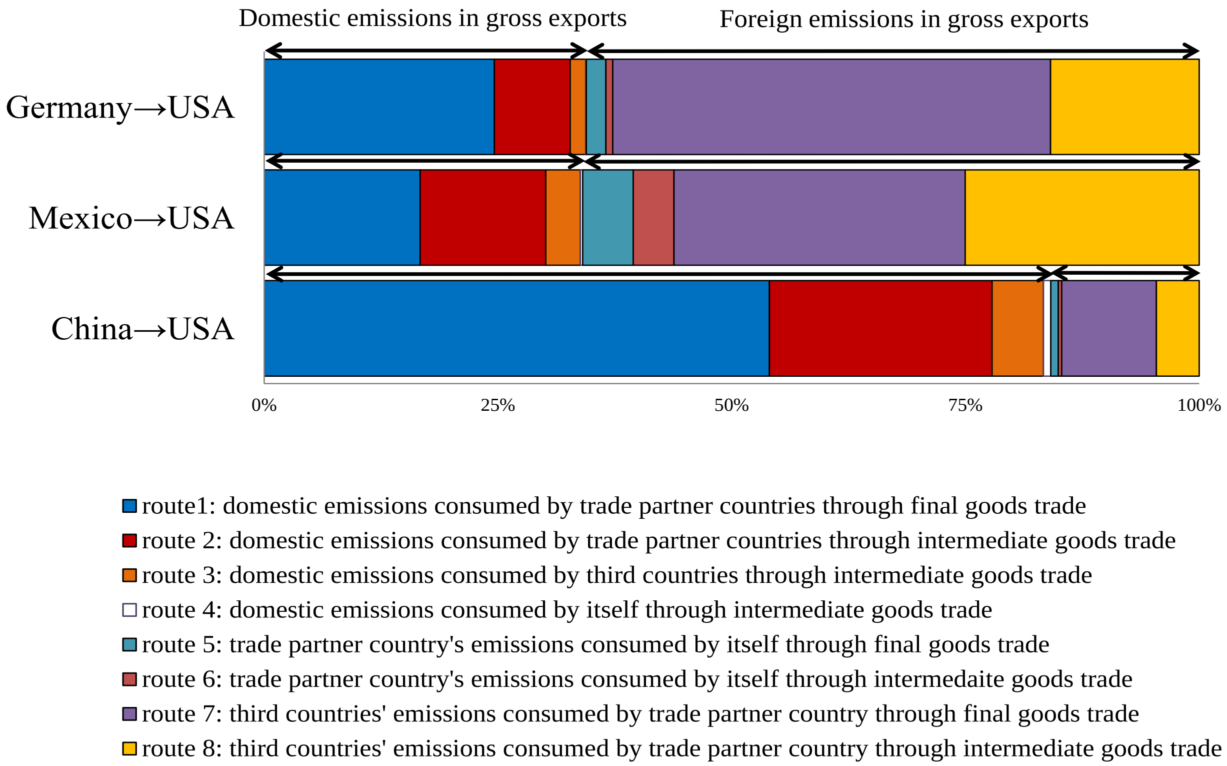
[1] China Daily, http://www.chinadaily.com.cn/bizchina/2010-01/12/content_9309129.htm, Updated: 2010-01-12 15:37

Figure 8 Induced foreign CO_2 emissions from producing cars in selected countries (backward industrial-linkage-based decomposition)



To illustrate how the accounting framework proposed in Figure 3 works at bilateral and sector levels, we use Germany, Mexico and China’s electrical product exports to the US as an example. Figure 9 demonstrates how a country’s gross exports of electrical products to the US generate both domestic and foreign CO_2 emissions through different GVC routes. These three countries were the largest trading partners for electrical products with the US in Europe, North America and Asia, respectively, in 2009. Figure 9 shows that about 85% of CO_2 emissions generated by China’s gross exports of electrical goods to the US are emitted inside China, a very large portion of which is from the production of final goods exported to the US. Compared to China, Germany and Mexico show a very different pattern. Their exports of electrical product to the US induce more foreign CO_2 emissions. This difference is caused by several reasons that may operate in opposing directions: for instance, a higher domestic carbon intensity in producing goods and services leads to a larger portion of domestic emissions; while a higher proportion of foreign intermediate imports in a country’s exports (implying a higher participation in GVCs), leads to a smaller portion of domestic emissions.

Figure 9 CO_2 emissions embodied in selected countries’ gross exports of electrical roducts shipped to the US via 8 different GVC routes (backward industrial-linkage-based decomposition, 2009)

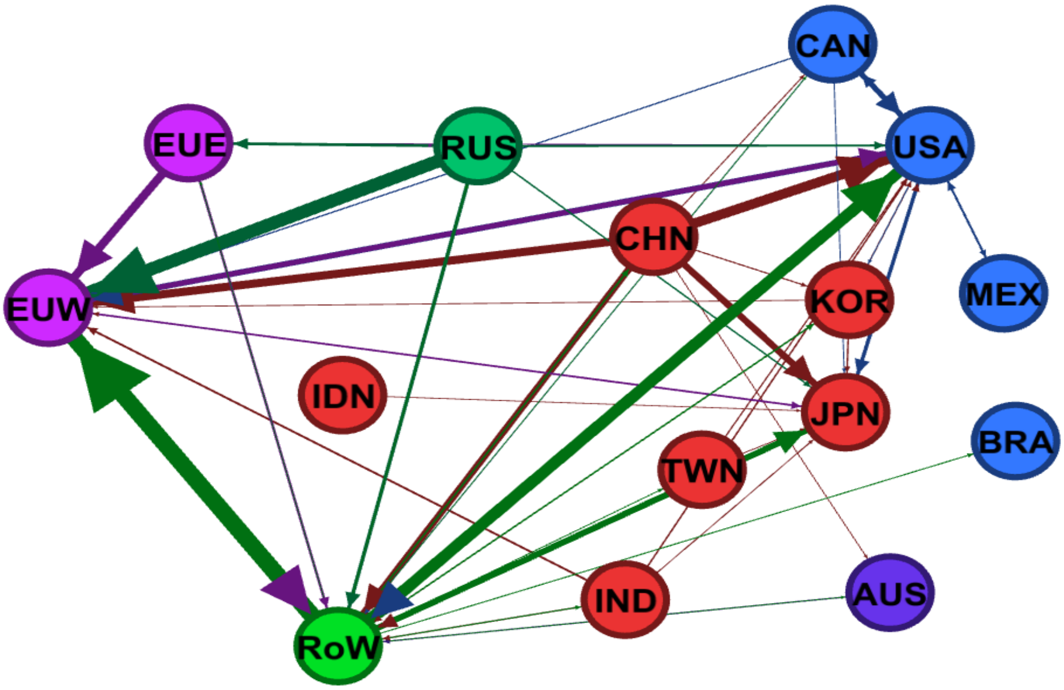


Estimates based on WIOD shows that the import contents of electrical product exports to the US are 24%, 53% and 32% for Germany, Mexico and China, respectively. Germany’s import contents are the lowest of these three exporting countries, but its gross exports to the US generate more foreign CO_2 emissions. This clearly reflects two factors. First, Germany has relatively low domestic carbon intensity in producing exports. Second, Germany may import more high-carbon intensity intermediate goods directly or indirectly from other countries for producing its gross exports to the US. Mexico's imported content in its exports is the highest. This naturally leads to a large portion of foreign CO_2 emissions in its gross exports. The US's CO_2 emissions generated by gross exports of electrical products from Mexico to the US accounts for a very large portion (routes 5 and 6) compared to that in other countries. This is mainly because Mexico needs more intermediate parts and components provided by the US directly or indirectly when producing electrical products for exporting back to the US. In addition, this accounting framework not only identify who produces gross exports and CO_2 emissions, but also identify who finally consumes the CO_2 emissions embodied in the gross exports. Clearly, the embodied CO_2 emissions in routes 1, 2, 5, 6, 7, and 8 are finally consumed by the US; emissions in route 3 are finally consumed by third countries, emissions in route 4 are finally consumed by the exporting countries themselves. The above example shows that border carbon adjustments would be difficult because emissions could be embodied in gross exports through different routes in GVCs due to different production sharing arrangements.

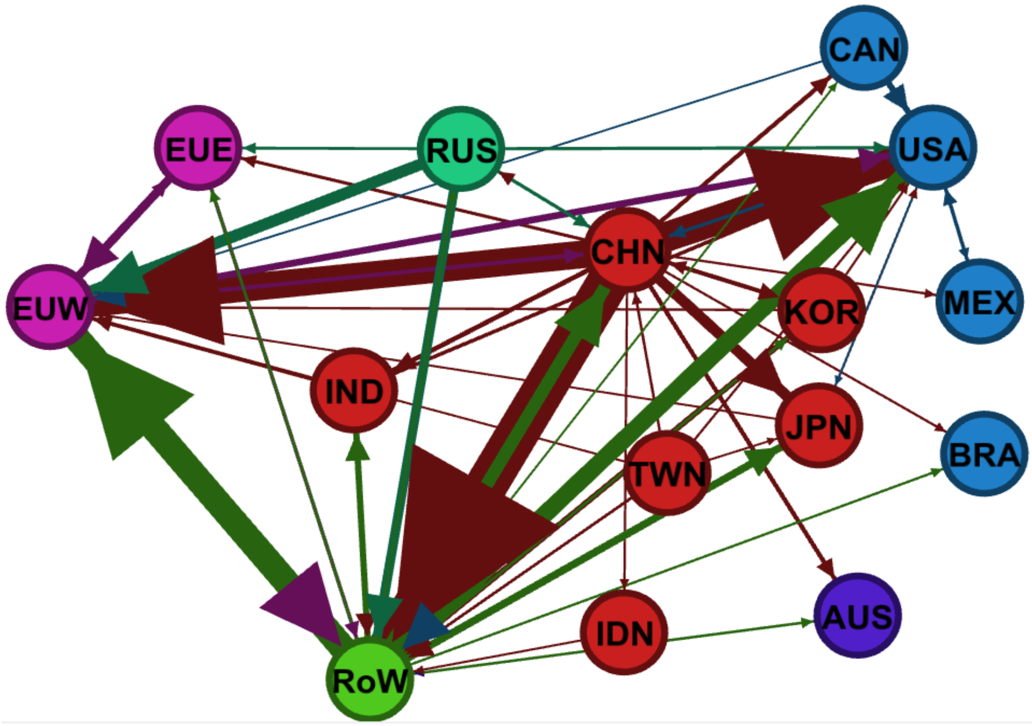
3.3 Bilateral Trade in CO_2 Emissions

Figure 10 shows the bilateral trade in CO_2 emissions across the 15 largest countries or country groups for 1995 and 2009. In 1995, China, the US, EUW (the EU15), Russia and the RoW are the major exporters of CO_2 emissions; Japan, the US, the EUW and the RoW are the major importers of CO_2 emissions. The basic direction of bilateral flows remains unchanged between 1995 and 2009, but some interesting changes in the magnitude of CO_2 emissions trade can be observed. For example, China's exports of CO_2 emissions increased dramatically and, at the same time, China also became one of the largest importers of CO_2 emissions. More interesting thing is that the carbon emission trade (exports + imports) between China and other developing countries has exceeded all bilateral emission trade between any developed economy blocks and China (the EU-China or the US-China). This is not only driven by the increased demand for Chinese manufacturing products from developing countries, but also due to “made in China” is highly depend on intermediate imports from other developing countries as inputs, and the RoW uses more and more intermediate imports from China, both of them have much higher carbon intensity than intermediate imports from developed countries. This could be a great concern since both China and countries in the RoW are Non-Annex B economies in Kyoto Protocol and have relatively weak environmental regulations.

Figure 10 Bilateral trade in CO_2 emissions



1995



20

09

Note: The magnitudes of emissions trade flows in this figure are based on EEX_F^{sr}. Exports from CHN (China) to the RoW (rest of the world) are respectively 104,563 Kt and 584,219 Kt for 1995 and 2009.

3.4 The relationship between GVC participation and embodied CO_2 emissions in gross exports

As mentioned in previous sections, a country's gross exports can generate both domestic and foreign CO_2 emissions through various GVC routes. The magnitudes of these two types of emissions highly depend on a country's position and participation in GVCs. The international economics literature on vertical specialization indicates that a country could join GVCs in two ways: it can participate in GVCs from downstream, use imported intermediate inputs to produce exports, or from upstream, exports intermediate goods that are used as inputs by another country to produce goods for exports. To determine a county's position in a vertical integrated production chain need both measures (Koopman et. al. 2014). Figure 11a shows the relationship between a country's GVC participation from downstream (similar to Hummels et al. (2001)'s vertical specialization share indictor labeled as VS, measures the value of imported contents embodied in a country's exports) and its domestic share of total CO_2 emissions embodied in gross exports for the top 20 exporting economies in the world in 2009. The size of a bubble represents the magnitude of foreign CO_2 emissions embodied in a country's gross exports. The dark the color of the bubble, the higher the emission intensity (environment cost for per unit GDP; emissions in KT / GDP in million US$ at 1995 constant prices). The rings with different colors surrounding the bubbles show four different GVC routes (through energy, non-energy final goods trade, energy, non-energy intermediate goods trade). The main facts revealed by Figure 11a can be summarized as follows.

1. The higher the imported content in a country's exports, the smaller the domestic CO_2 emissions in its gross exports (ceteris paribus). When a country uses more foreign intermediate inputs to substitute for domestic inputs in producing exports, relatively less CO_2 emissions will be generated domestically[1]. The large scale of gross exports produced by China and the RoW and their relatively higher imported contents in

---

[1] Without considering the energy goods trade, the level of GVC participation for the RoW should be much lower.

exports compared to similar large countries, such as the US and Japan, cause more foreign CO_2 emissions. However, the relatively higher carbon intensity for developing economies, like China, India and the RoW, leads to a larger share of domestic CO_2 emissions embodied in their gross exports, although their shares of imported contents in exports are similar to some developed economies, such as Germany, France and Spain.

2. Developing economies join GVCs by providing relatively more final goods, which is different from developed economies due to their different comparative advantages. For example, the foreign CO_2 emissions embodied in gross exports from the US, Japan, Korea and Taiwan are mainly as a result of intermediate goods trade, while for China, India and Mexico they are mainly as a result of final goods trade.

3. China and RoW have been the top two regions inducing massive foreign CO_2 emissions in producing exports. Besides their large scale of gross exports, both economies import high-carbon intensity components from each other. While Japan, Korea and Taiwan's bubbles are not only relatively large but also darker (higher carbon intensity). This is mainly because China has been their major trading partner, providing not just final goods but also intermediate goods.

Figure 11a The relationship between GVC participation and CO2 emissions (2009)

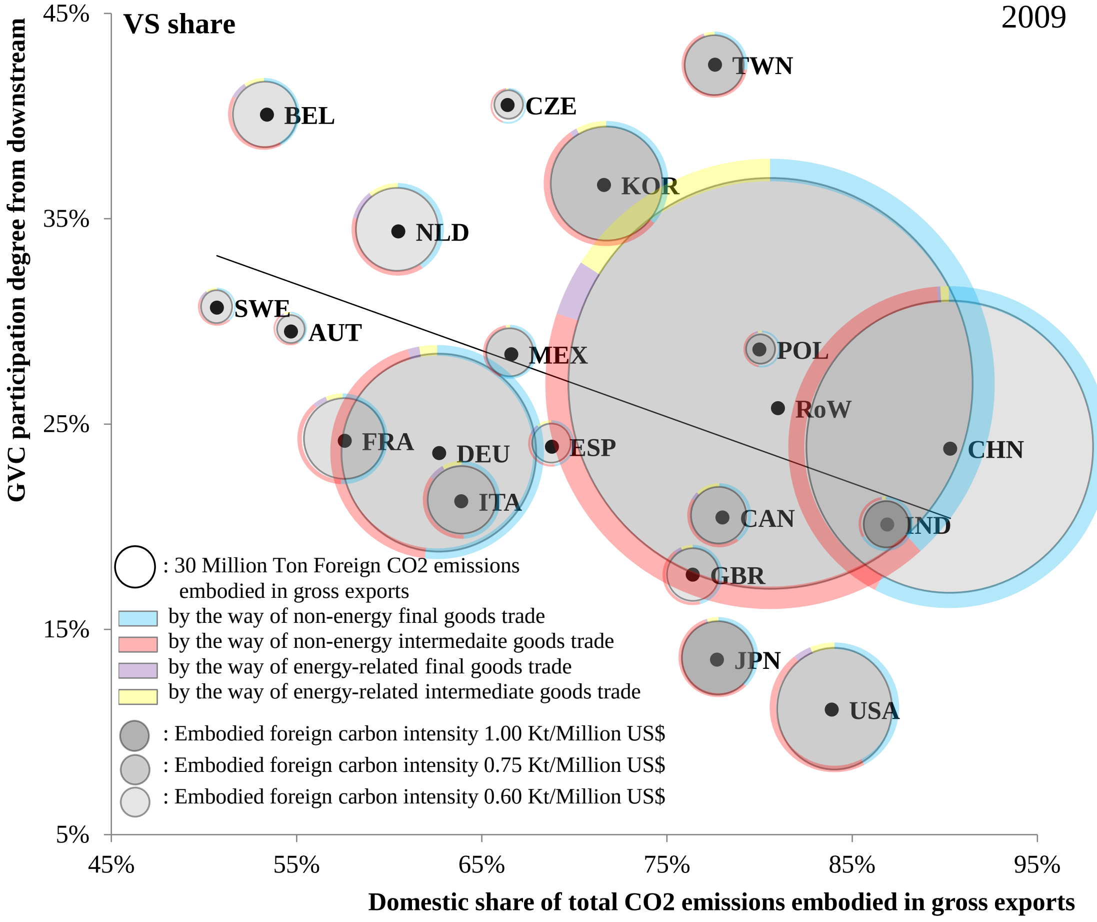
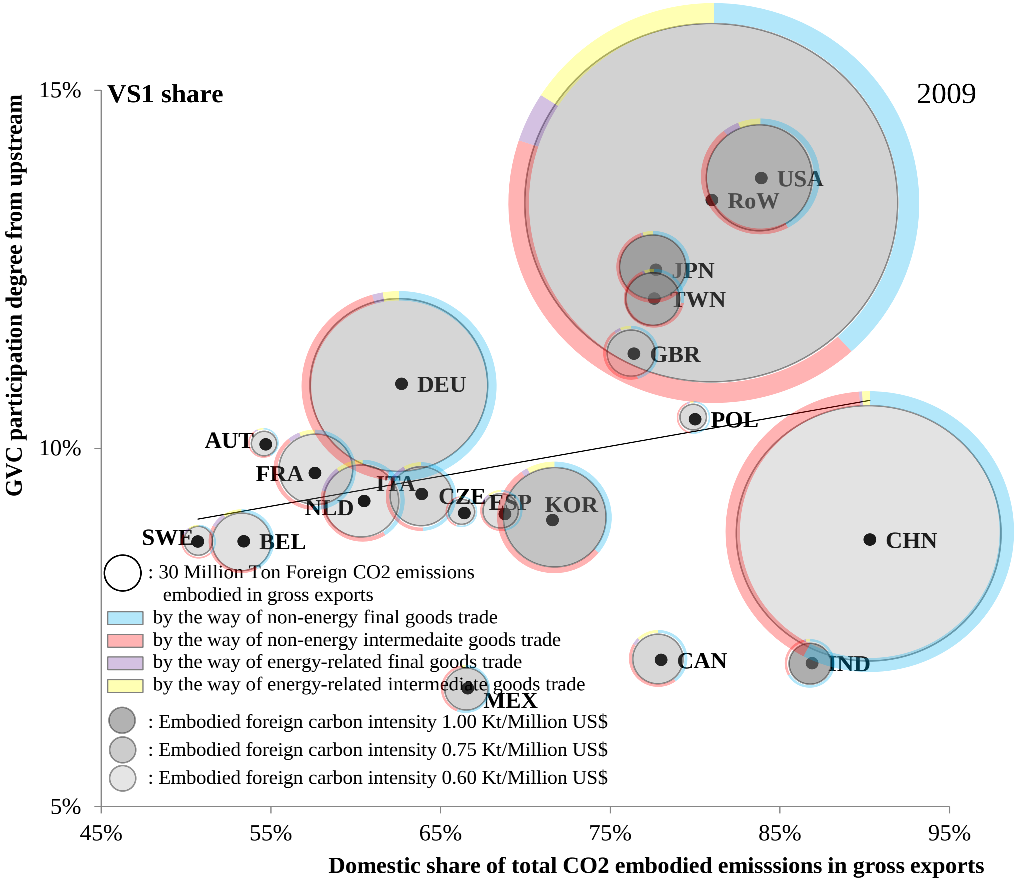


Figure 11b shows the relationship between a country's GVC participation from upstream (similar to Hummels et al. (2001)'s vertical specialization share indictor labeled as VS1, measures intermediate exports sent indirectly through other countries) and its domestic share of total CO_2 emissions embodied in gross exports. The horizontal axis remains no change, but countries' positions show very different pattern compared to that in Figure 11a. For example, because developed economies, such as the US, Japan, UK, Germany and Taiwan can provide more sophisticated manufacturing intermediates to their downstream countries for further processing and assembling, thus have higher degree of GVC participation from upstream, while India, Mexico and China have lower levels of participation. Viewing a country's participation from both upstream and downstream perspective provide more insights on the relationship between GVC participation and emissions in trade. For instance, Korea and Taiwan's positions are very close in Figure 11a, but very different in Figure 11b.

Figure 11b The relationship between GVC participation and CO_2 emissions (2009)



3.5 Consumption-based versus production-based CO_2 emissions and emissions transfer through different GVC routes

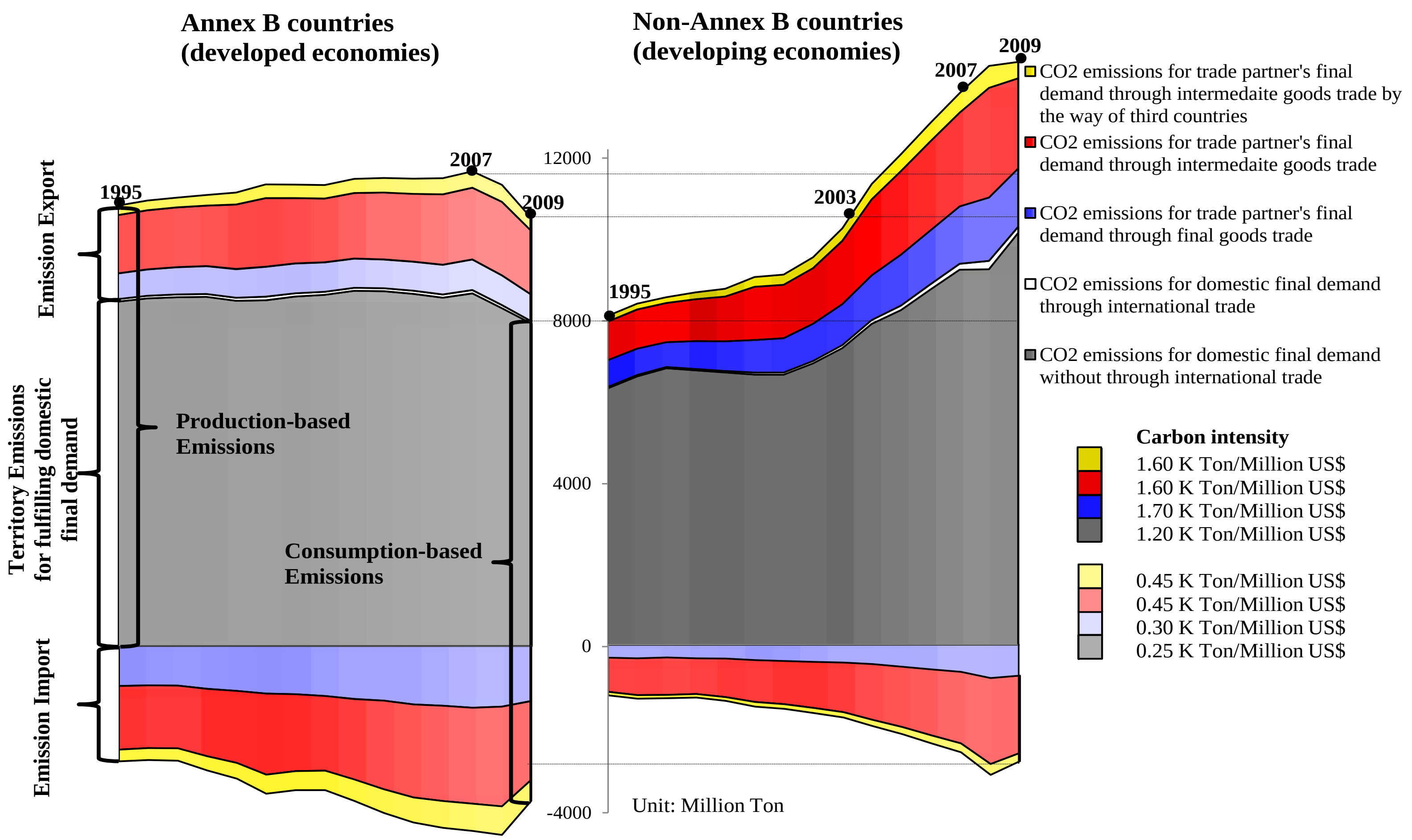
As shown by Peters et al. (2011), most developed countries (as Annex B countries in the Kyoto Protocol) have increased their consumption-based CO_2 emissions faster than their territorial emissions. The net emissions transfer via international trade from developing to developed countries increased very rapidly and exceeds the Kyoto Protocol emissions reduction. Expanding on Peters et al. (2011) (use the forward industrial-linkage-based decomposition method summarized by Figure 1), we not only estimate the consumption-based and production-based emissions and their evolution from 1995 to 2009 for both Annex B and Non-Annex B country groups, but also further investigate how the international transfer of emissions occurs through various GVC routes with different environmental costs (carbon intensities).

Figure 12 shows that production-based CO_2 emissions for the Annex B country group have increased slightly in the period 1995-2009. Emission exports for satisfying foreign final demands is the main driver of this increase, since territory emissions for fulfilling domestic final demands have shown a slight decrease in the same period. Consumption-based emissions for the Annex B country group experienced an increase due to increasing emissions imports (foreign emissions induced by Annex B countries). Looking at the structure of Annex B countries’ increasing emissions trade by different GVC routes, we find that trade in intermediate goods is the main contributor to growth for both exports and imports, with little change in trade through final goods except for a slight increasing trend for imports. Compared to the Annex B countries, the Non-Annex

B country group shows large increases in both domestic emissions and emissions trade. The production-based emissions for the Non-Annex B group in 2003 exceeded the Annex B group's peak level emissions (2007); Non-Annex B group's territory emissions for its domestic final demands in 2009 were close to the level of production-based emissions for Annex B groups. The Non-Annex B country group also imports more emissions and has been at the same level as the Annex B group's emissions exports.

With the information about carbon intensity (the dark the color, the higher the emission intensity with higher environment cost for per unit GDP; emissions in KT / GDP in million US$ at 1995 constant prices) along different GVC routes, the major facts observed from Figure 12 can be summarized as follows:

Figure 12 Consumption-based vs. production-based CO2 emissions and emissions transfer through different GVC routes (1995-2009)



1. The environmental cost for generating one unit GDP in domestic production networks is lower than that through international trade for both developed and developing countries. One of the main drivers is the carbon leakage through international trade due to differences in environmental regulation level across countries. Another driver is the increasing fragmentation of production, which requires more international transportation shipment (high-carbon intensity sector) across multiple borders multiple times.
2. The environmental cost for generating one unit GDP shows a decreasing trend for both Annex B and Non-Annex B counties from 1995 to 2009. However, the carbon intensity for Non-Annex B countries in 2009 is still higher than that for Annex B countries' 1995 level. In addition, the decrease on carbon intensity[1] in developing economies cannot offset the increased emissions from rapid economic and population growth. This clearly implies that helping more developing countries set carbon emission peak as China did in 2014 is more urgent than decades ago.
3. The increasing sophistication in cross country production sharing also give an impetus to emissions transfer, since more cross-border CO_2 emissions transfer arises through intermediate goods trade via third countries.

3.6 The hidden environment cost of China's comparative advantage in manufacturing exports

As discussed in section 2, different measures of emission defined in this paper provide different tools to quantify embodied CO_2 emissions trades from different perspectives[2]. To provide a better understanding of the differences between these

---

[1] For detailed empirical results on carbon intensity at the bilateral level by different energy types along GVCs, one can refer to Figure B3 in Appendix.

[2] Table B5 in Appendix B reports bilateral embodied emissions trade of Electrical and Optical Equipment (WIOD sector 14) between China and Japan in 2009 by different measures defined in section 2. It is a numerical example to illustrate the analytical relations among various emission trade measures we discussed in table 1b in real world data.

measures and their economic and policy implications, we use both the forward and the backward industrial-linkage-based domestic emission measure to compute China's Released Comparative Advantage (RCA[1]) as an example.

The traditional RCA indicator (Balassa 1966) is based on gross exports. As pointed by Wang et al. (2013), the traditional RCA ignores both domestic production sharing and international production sharing. A conceptually correct measure of comparative advantage needs to exclude foreign-originated value added and pure double counted terms in gross exports but include indirect exports of a sector's value added through other sectors of the exporting country. When a country uses imported intermediate goods intensively to produce its exports, Koopman et al. (2014) show that RCA based on gross exports can be very misleading and suggested a way to remove the distortion of double counting by focusing on domestic value-added in exports. We follow the same idea here to measure a country's RCA by using both value-added exports and CO_2 emissions exports. As mentioned earlier, according to the forward industrial-linkage-based decomposition, a country's value-added or CO_2 emissions exports at the sector level represent how much of this country's specific sector's value-added or CO_2 emissions embodied in all downstream countries' and sectors' gross output is finally consumed in foreign countries. According to the backward industrial-linkage-based decomposition, a country's value-added or CO_2 emissions exports at the sector level measures how much this country's value-added or CO_2

---

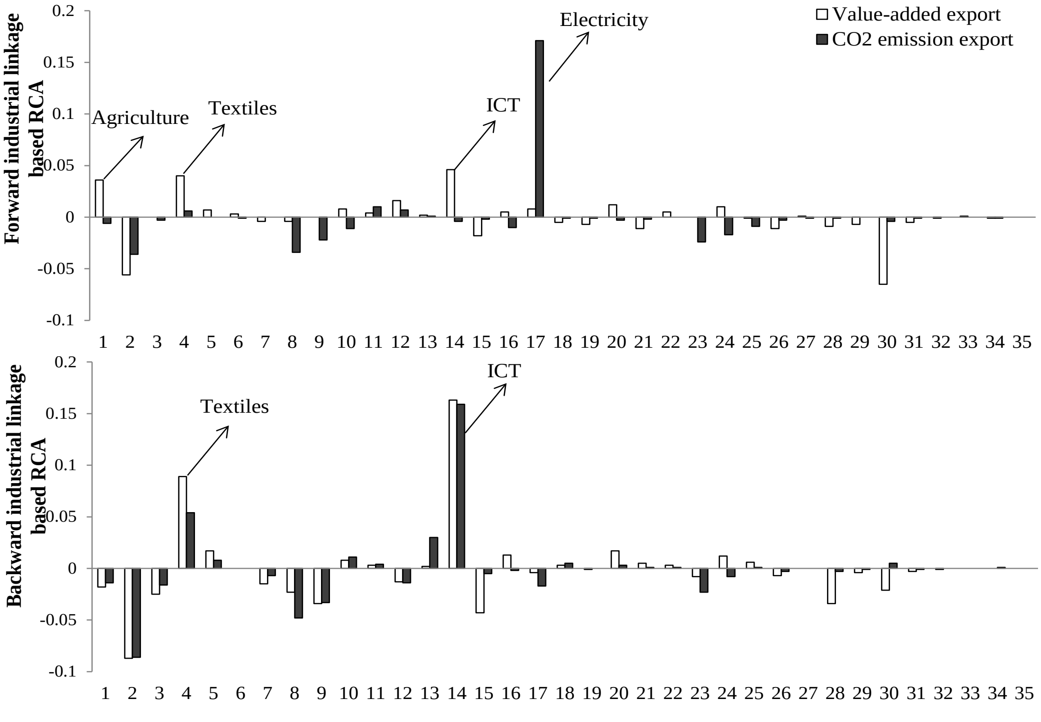
[1] The RCA indicator used in the paper follows the additional RCA measure proposed by Hoen and Oosterhaven (2006). This type of indicator ranks from -1 to +1, with a symmetric distribution that centers on a stable mean of zero, independent of the sector classifications used.

emissions in all upstream production stages are embodied in a specific product that is finally consumed in foreign countries.

The upper penal of Figure 13 shows China's forward industrial linage based RCA by sector ranking for both value-added and CO_2 emissions exports. For value-added exports, Electrical and Optical Equipment (ICT, WIOD sector 14), Textiles and Textile Products (WIOD sector 4) and Agriculture, Hunting, Forestry and Fishing (WIOD sector 1) show the highest RCA since all these sectors generate more value-added for fulfilling foreign countries' final demand through global value chains directly and indirectly. However, for CO_2 emissions exports, these Chinese products are relative cleaner, only Electricity, Gas and Water Supply (sector 17) shows an extremely high RCA. This implies that energy sector emits large amounts of CO_2 emissions embodied in China's various manufacturing exports to satisfy foreign final demands, which are not show up in traditional trade statistics since there is a negligible amount of Chinese electricity exported directly.

The bottom penal of Figure 13 shows the backward industrial linkage based RCA estimates for China. Clearly, the RCA for value-added export is normally consistent to that for CO2 emissions export at the sector level. The production of Chinese textile and ICT exports is much more carbon intensive due to its upstream sectors (such as electricity, metal, glass production) are more carbon intensive than most developed countries. We see that from the perspective of a producer, the production process of these Chinese products has a low-carbon intensity (forward), but from the viewpoint of foreign user, they have a high-carbon intensity since relatively large shares of CO2 emissions are generated in their upstream sectors (backward). This implies that both downstream-driven and upstream-driven RCA indicators have their own roles in helping better understanding the fact that China's comparative advantage in many manufacturing sectors in the world market are highly related to high-carbon inputs coming from their upstream sectors, which have little direct exports in the traditional trade statistics, but is embodied in other Chinese manufacturing products and in fact indirectly exports to the world market extensively.

Figure 13 Backward vs. forward industrial linkage based RCA for both value-added exports and CO_2 emissions exports (2009)



4. Concluding remarks

The rise of global value chains has dramatically changed the nature and structure of international trade in recent decades. There is particularly strong growth in intermediate goods and services that may cross borders multiple times before the delivery of final products. This makes it difficult to understand “who produces value for whom” in a fragmented production system, compared to the relatively simple situation in the Ricardian era where exports were mainly final goods. The increasing complexity of GVCs has produced challenges for economic and environment policy as well as international governance. Therefore, it is important to understand to what extent GVCs impact on both value creation and emissions generation for trade and environment policies.

This paper unifies and extends existing emissions trade related measures, quantify their relationships, and further combines them with trade in value-added and GVC-based measures in recent literature into one consistent accounting framework, in which both value added and emissions can be systematically traced at country, bilateral, and sector levels through various GVC routes. In principle, when new countries or years are added to the WIOD database, or an alternative inter-country input-output table becomes available, our accounting framework can be applied as well. So the accounting framework developed in this paper is not inherently tied to the WIOD database and can be a stand-alone tool. It provides a useful analytical method for both trade and environment economists as well as policy makers to study the impact of production fragmentation and emergence of GVCs on the environment. We show that conventional analysis on carbon emission transfer, shared responsibilities and the environment cost of a country’s comparative advantages can all benefit from applying such new analytical tool developed in this paper.

Better and detailed information that combine environment cost and economic benefit in each production stages and trade routes along GVCs provide useful insights regarding to the role of each specific trade route in emission transfer and scientific evidence for concrete, targeted incentive mechanism and an integrated trade and greenhouse gas emission reduction policy design. We leave further analysis of the full decomposition results (it takes up 20 gigabytes of space) and link it to policy design for our future research agenda.

References

[1]. Andrew, R.M. and Peters, G.P. (2013). A multi-region input-output table based on the Global Trade Analysis Project Database (GTAP-MRIO). *Economic Systems Research* 25 (1): 99-121.

[2]. Antràs, P. and Chor, D. (2013). Organizing the global value chain. *Econometrica*, 81(6): 2127-2204.

[3]. Arto, I. and Dietzenbacher, E. (2014). Drivers of the growth in global greenhouse gas emissions. *Environmental Science & Technology* 48(10): 5388−5394.

[4]. Atkinson, G., Hamilton, K., Ruta, G., Mensbrugghe, D. van der (2011). Trade in 'virtual carbon': Empirical results and implications for policy. *Global Environmental Change* 21(2): 563-574.

[5]. Atkinson, G., (2013). EU corporate action as a driver for global emissions abatement: A structural analysis of EU international supply chain carbon dioxide emissions. *Global Environmental Change* 23(3): 1795-1806.

[6]. Balassa, B. (1965). Trade Liberalization and Revealed Comparative Advantage. *the Manchester School*, 33 (2): 99-123.

[7]. Baldwin, R. (2012). WTO 2.0: Global governance of supply-chain trade. *CEPR Policy Insight* 64.

[8]. Baldwin, R. and Robert-Nicoud, F. (2014). Trade-in-goods and trade-in-tasks: An integrating framework. *Journal of International Economics* 92(1): 51-62.

[9]. Bastianoni, S., Pulselli, F.M., Tiezzi, E. (2004). The problem of assigning responsibility for greenhouse gas emissions. *Ecological Economics* 49: 253-257.

[10]. Cadarso, M.A., Lopez, L.A., Comez, N., Tobarra, M.A. (2012). International trade and shared environmental responsibility by sector. An application to the Spanish economy. *Ecological Economics* 83: 221-235.

[11]. Davis, S.J. and Caldeira, K. (2010). Consumption-based accounting of CO_2 emissions. *PNAS* 107(12): 5687-5692.

[12]. Davis, S.J., Peters, G.P., and Caldeira, K. (2011). The supply chain of CO_2 Emissions. *PNAS* 108 (45): 18554-18559.

[13]. de Haan, M. and Keuning, S. J. (1996). Taking the environment into account: The NAMEA approach. *Review of Income and Wealth* 42: 131-148.

[14]. de Haan, M. and Keuning, S. J. (2001). The NAMEA as validation instrument for environmental macroeconomics. *Integrated Assessment* 2: 79-87.

[15]. Ferrarini, B. and D. Hummels, eds. (2014) *Asia and Global Production Networks –Implications for Trade, Incomes and economic Vulnerability*. Edward Elgar.

[16]. Feng, J.J. (2003) Allocating the responsibility of CO2 over-emissions from the perspectives of benefit principle and ecological deficit. *Ecological Economics* 46: 121-141.

[17]. Grossman, G.M., Rossi-Hansberg, E. (2008). Trading tasks: a simple theory of offshoring. *The American Economic Review* 98(5): 1978-1997.

[18]. Hertwich, E.G. and Peters, G.P. (2009). Carbon footprint of nations: A global, trade-linked analysis. *Environmental Science and Technology* 43 (16): 6414-6420.

[19]. Hoekstra, A. and Mekonnen, M. (2012). The water footprint of humanity, PANS, 109(9), 3232-3237.

[20]. Hoekstra, A. and Wiedmann, T. (2014). Humanity's unsustainable environmental footprint. *Science* 344(6188): 1114-1117.

[21]. Hoen, A.R. and Oosteraven, J. (2006). On the measurement of comparative advantage. *The Annals of Regional Science* 40: 677-691.

[22]. Hummels, D., Ishii, J., Yi, K.M. (2001). The nature and growth of vertical specialization in world trade. *Journal of International Economics* 54 (1): 75-96.

[23]. Johnson, R. and Noguera, G. (2012). Accounting for Intermediates: Production Sharing and Trade in Value added. *Journal of International Economics* 86: 224-236.

[24]. Kanemoto, K., Lenzen, M., Peters, G.P., Moran, D., Geschke, A. (2012). Frameworks for comparing emissions associated with production, consumption, and international trade. *Environmental Science and Technology* 46: 172-179.

[25]. Koopman, R., Wang, Z., Wei, S.J. (2014). Tracing value-added and double counting in gross exports. *American Economic Review* 104(2): 459-494.

[26]. Lenzen, M., Moran, D, Kanemoto, K., Foran, B., Lobefaro, L., Geschke, A. (2012), International trade drives biodiversity threats in developing nations. *Nature* 486: 109-112.

[27]. Lenzen, M., Murray, J., Sack, F., Wiedmann, T. (2007). Shared producer and consumer responsibility － theory and practice. *Ecological Economics* 61: 27-42.

[28]. Leontief, W. (1936). Quantitative input and output relations in the economic system of the United States. *The Review of Economic and Statistics* 18: 105-25.

[29]. Lin, J., Pan, D., Davis, S.J., Zhang, Q., He, K., Wang, C., Streets, D.G., Wuebbles, D.J., Guan, D. (2014). China's international trade and air pollution in the United States. *PNAS* 111(5): 1736-1741.

[30]. Meng, B., Xue, J., Feng, K., Guan, D., Fu, X. (2013). China's inter-regional spillover

of carbon emissions and domestic supply chains. *Energy Policy* 61: 1305-1321.

[31]. OECD, WTO and UNCTAD (2013) “Implications of Global Value Chains for Trade, Investment Development and Jobs” prepared by OECD, WTO and UNCTAD for the G20 Leaders Summit, St. Petersburg, Russian Federation September.

[32]. Pedersen, G.O. and de Haan, M. (2006). The system of environmental and economic accounts-2003 and the economic relevance of physical flow accounting. *Journal of Industrial Ecology* 10: 19-42.

[33]. Peters, G.P., and Hertwich, E.G. (2006). The importance of imports for household environmental impacts. *Journal of Industrial Ecology* 10 (3): 89-109.

[34]. Peters, G.P. (2008). From production-based to consumption-based national emission inventories. *Ecological Economics* 65: 13-23.

[35]. Peters, G.P. and Hertwich, E.G. (2008). CO2 embodied in international trade with implications for global climate policy. *Environmental Science and Technology*, 42 (5): 1401-1407.

[36]. Peters, G.P., Minx, J.C., Weber, C.L., Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008. *PANS* 108(21): 8903-8908.

[37]. Peters, G.P., Davis, S.J., Andrew, R. (2012). A synthesis of carbon in international trade. *Biogeosciences* 9: 3247–3276.

[38]. Rodrigues, J., Domingos, T., Giljum, S., Schneider, F. (2006). Designing an indicator of environmental responsibility. *Ecological Economics* 59: 256-266.

[39]. Timmer, M.P., Dietzenbacher, E., Los, B., Stehrer, R., de Vries,G.J. (2014a). The World Input-Output Database (WIOD): Contents, concepts and applications. *GGDC Research Memorandum* 144. Groningen Growth and Development Centre.

[40]. Timmer, M.P., Erumban, A.A., Los, B., Stehrer, R., De Vries, G.J., (2014b). Slicing up global value chains. *Journal of Economic Perspectives* 28(2): 99-118.

[41]. Timmer, M. P., Los, B., Stehrer, R. and de Vries, G. J. (2013). Fragmentation, incomes and jobs: an analysis of European competitiveness. *Economic Policy* 28(76): 613–661.

[42]. Tukker, A. and Dietzenbacher, E. (2013). Global multiregional input–output frameworks: An introduction and outlook. *Economic Systems Research* 25(1): 1-19.

[43]. Wang, Z., Wei, S.J., Zhu, K. (2013). Quantifying international production sharing at the bilateral and sector levels. *NBER Working Paper* 19677.

[44]. Weinzettel, J., Hertwich, E.G., Peters, G.P., Steen-Olsen, K., Galli, A. (2013). Affluence drives the global displacement of land use. *Global Environmental Change* 23(2):

433-438.

[45]. Wiedmanna, T.O., Schandlb, H. Lenzen, M., Moranc, D., Suh, S., West, J., Kanemoto, K. (2013). The material footprint of nations. *PANS.*

[46]. Yi, K.M. (2010). Can multistage production explain the Home Bias in trade? *The American Economic Review* 100(1): 364-393.

Tracing Greenhouse Gas Emissions in Global Value Chains

Bo MENG, Glen PETERS, and Zhi WANG

Appendix

Appendix A [1]

A.1 Step by step proof of Equation (10) in the main text

Write $L^{ss} = (I - A^{ss})^{-1}$, then the last term of equation (9) in the main text can be written as

$$L^{ss}E^{s*} = L^{ss}\Big(\sum_{r \neq s}^{G} Y^{sr} + \sum_{r \neq s}^{G} A^{sr} X^{r}\Big) \tag{A1}$$

Using the gross output X^r decomposition equation

$$X^{r} = \sum_{t}^{G} B^{rt} \sum_{u}^{G} Y^{tu} \ ,$$

E^{s*} can be expressed as

$$\begin{aligned} E^{s*} &= \sum_{r \neq s}^{G} Y^{sr} + \sum_{r \neq s}^{G} A^{sr} \sum_{t}^{G} B^{rt} \sum_{u}^{G} Y^{tu} \\ &= \sum_{r \neq s}^{G} Y^{sr} + \sum_{r \neq s}^{G} A^{sr} B^{rs} \sum_{t \neq s}^{G} Y^{st} + \sum_{r \neq s}^{G} A^{sr} \sum_{t \neq s}^{G} B^{rt} Y^{tt} + \sum_{r \neq s}^{G} A^{sr} \sum_{t \neq s}^{G} B^{rt} \sum_{u \neq s,t}^{G} Y^{tu} \\ &\quad + \sum_{r \neq s}^{G} A^{sr} \sum_{t \neq s}^{G} B^{rt} Y^{ts} + \sum_{r \neq s}^{G} A^{sr} B^{rs} Y^{ss} \end{aligned} \tag{A2}$$

Rearranging gives

$$\begin{aligned} E^{s*} &= \sum_{r \neq s}^{G} Y^{sr} + \sum_{t \neq s}^{G} A^{st} B^{ts} \sum_{r \neq s}^{G} Y^{sr} + \sum_{t \neq s}^{G} A^{st} \sum_{r \neq s}^{G} B^{tr} Y^{rr} + \sum_{t \neq s}^{G} A^{st} \sum_{u \neq s,r}^{G} B^{tu} \sum_{r \neq s}^{G} Y^{ur} \\ &\quad + \sum_{t \neq s}^{G} A^{st} \sum_{r \neq s}^{G} B^{tr} Y^{rs} + \sum_{t \neq s}^{G} A^{st} B^{ts} Y^{ss} \end{aligned} \tag{A3}$$

Inserting equation (A3) into (A1) gives

---

[1] We acknowledge Dr. Kunfu Zhu’s help on related mathematical derivations.

$$\begin{aligned} L^{ss}E^{s*} &= \left(L^{ss} + L^{ss}\sum_{t\neq s}^{G} A^{st}B^{ts} \right)\sum_{r\neq s}^{G} Y^{sr} + L^{ss}\sum_{t\neq s}^{G} A^{st}\sum_{r\neq s}^{G} B^{tr}Y^{rr} + L^{ss}\sum_{u\neq s}^{G} A^{su}\sum_{t\neq s,r}^{G} B^{ut}\sum_{r\neq s}^{G} Y^{tr} \\ &+ L^{ss}\sum_{t\neq s}^{G} A^{st}\sum_{r\neq s}^{G} B^{tr}Y^{rs} + L^{ss}\sum_{t\neq s}^{G} A^{st}B^{ts}Y^{ss} \end{aligned} \tag{A4}$$

Using the properties of inverse matrices, we can obtain the identity

$$\begin{aligned} &\begin{bmatrix} I-A^{11} & -A^{12} & \cdots & -A^{1G} \\ -A^{21} & I-A^{22} & \cdots & -A^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ -A^{G1} & -A^{G2} & \cdots & I-A^{GG} \end{bmatrix} \begin{bmatrix} B^{11} & B^{12} & \cdots & B^{1G} \\ B^{21} & B^{22} & \cdots & B^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ B^{G1} & B^{G2} & \cdots & B^{GG} \end{bmatrix} = \begin{bmatrix} I & 0 & \cdots & 0 \\ 0 & I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & I \end{bmatrix} \\ &= \begin{bmatrix} B^{11} & B^{12} & \cdots & B^{1G} \\ B^{21} & B^{22} & \cdots & B^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ B^{G1} & B^{G2} & \cdots & B^{GG} \end{bmatrix} \begin{bmatrix} I-A^{11} & -A^{12} & \cdots & -A^{1G} \\ -A^{21} & I-A^{22} & \cdots & -A^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ -A^{G1} & -A^{G2} & \cdots & I-A^{GG} \end{bmatrix} \end{aligned} \tag{A5}$$

From (A5) we obtain

$$(I-A^{ss})B^{sr} - \sum_{t\neq s}^{G} A^{st}B^{tr} = 0 \tag{A6}$$

$$(I-A^{ss})B^{ss} - \sum_{r\neq s}^{G} A^{sr}B^{rs} = I = B^{ss}(I-A^{ss}) - \sum_{r\neq s}^{G} B^{sr}A^{rs} \tag{A7}$$

From equations (A6) and (A7), we can obtain flow relationships between global block inverse matrices and local inverse matrices:

$$\begin{aligned} &B^{ss} = L^{ss} + L^{ss}\sum_{t\neq s}^{G} A^{st}B^{ts}\,,\quad B^{sr} = L^{ss}\sum_{t\neq s}^{G} A^{st}B^{tr}\,, \\ &B^{st} = L^{ss}\sum_{r\neq s}^{G} A^{sr}B^{rt}\,,\quad L^{ss}\sum_{t\neq s}^{G} A^{st}B^{ts} = \sum_{r\neq s}^{G} B^{sr}A^{rs}L^{ss} \end{aligned}$$

Inserting these four equations into (A4) gives

$$L^{ss}E^{s*} = B^{ss}\sum_{r\neq s}^{G} Y^{sr} + \sum_{r\neq s}^{G} B^{sr}Y^{rr} + \sum_{r\neq s}^{G} B^{sr}\sum_{t\neq s,r}^{G} Y^{rt} + \sum_{r\neq s}^{G} B^{sr}Y^{rs} + \sum_{r\neq s}^{G} B^{sr}A^{rs}L^{ss}Y^{ss} \tag{A8}$$

which is exactly the same as equation (10) in the main text. We can further show that

$$\sum_{r\neq s}^{G} B^{sr}Y^{rs} + \sum_{r\neq s}^{G} B^{sr}A^{rs}L^{ss}Y^{ss} = \sum_{t\neq s}^{G} A^{st}\sum_{r\neq s}^{G} B^{tr}Y^{rs} + \sum_{t\neq s}^{G} A^{st}B^{ts}Y^{ss} = \sum_{t\neq s}^{G} A^{st}\sum_{r}^{G} B^{tr}Y^{rs} \tag{A9}$$

A.2 Step by step proofs of Equations (18), (19) and (20) in the main text

As equation (1) in the main text shows, the gross exports of country *s* to country *r* can be decomposed into two parts: final goods exports and intermediate goods exports,

$$E^{sr} = Y^{sr} + A^{sr} X^{r} \tag{A10}$$

As illustrated in section 2.1 in the main text, final goods exports can be easily decomposed into domestic and foreign value added by directly applying Leontief’s insight. However, the decomposition of intermediate goods exports is more complex. It cannot be achieved by simply multiplying the Leontief inverse with gross intermediate exports because the latter has to be solved from the MRIO models first for any given level of final demand. Wang et al. (2013) provide a method to overcome this endogeneity issue by expressing all intermediate trade flows as different countries’ final demands according to where the goods or services are absorbed. Following their method, the gross output of country *r* can be decomposed into the following components according to where it is finally absorbed (obtained from equation (12) in the main text by pick-up country *r* only):

$$\begin{aligned} X^{r} &= \sum_{t}^{G} B^{rt} \sum_{u}^{G} Y^{tu} = B^{rr} \sum_{t}^{G} Y^{rt} + \sum_{t\neq s,r}^{G} B^{rt} \sum_{u\neq s,t}^{G} Y^{tu} + B^{rs} \sum_{t\neq s}^{G} Y^{st} \\ &= \sum_{r\neq s}^{G} B^{rr} Y^{rr} + \sum_{r\neq s}^{G} \sum_{t\neq s,r}^{G} B^{rt} Y^{tt} + \sum_{r\neq s}^{G} B^{rr} \sum_{t\neq s}^{G} Y^{rt} + \sum_{r\neq s}^{G} \sum_{t\neq s,r}^{G} B^{rt} Y^{tr} \\ &+ \sum_{r\neq s}^{G} \sum_{t\neq s,r}^{G} B^{rt} \sum_{u\neq s,r,t}^{G} Y^{tu} + \sum_{r\neq s}^{G} \sum_{t\neq s}^{G} B^{rt} Y^{ts} + \sum_{r\neq s}^{G} B^{rs} Y^{ss} + \sum_{r\neq s}^{G} B^{rs} Y^{sr} + \sum_{r\neq s}^{G} B^{rs} \sum_{t\neq s,r}^{G} Y^{st} \end{aligned} \tag{A11}$$

Inserting equation (A11) into the last term of equation (A10), the gross intermediate exports of country *s* to country *r* can be fully decomposed according to where they are absorbed:

$$\begin{aligned} A^{sr} X^{r} &= \sum_{r\neq s}^{G} A^{sr} B^{rr} Y^{rr} + \sum_{r\neq s}^{G} A^{sr} \sum_{t\neq s,r}^{G} B^{rt} Y^{tt} + \sum_{r\neq s}^{G} A^{sr} B^{rr} \sum_{t\neq s}^{G} Y^{rt} + \sum_{r\neq s}^{G} A^{sr} \sum_{t\neq s,r}^{G} B^{rt} Y^{tr} \\ &+ \sum_{r\neq s}^{G} A^{sr} \sum_{t\neq s,r}^{G} B^{rt} \sum_{u\neq s,r,t}^{G} Y^{tu} + \sum_{r\neq s}^{G} A^{sr} \sum_{t\neq s}^{G} B^{rt} Y^{ts} + \sum_{r\neq s}^{G} A^{sr} B^{rs} Y^{ss} + \sum_{r\neq s}^{G} A^{sr} B^{rs} Y^{sr} + \sum_{r\neq s}^{G} A^{sr} B^{rs} \sum_{t\neq s,r}^{G} Y^{st} \end{aligned}$$

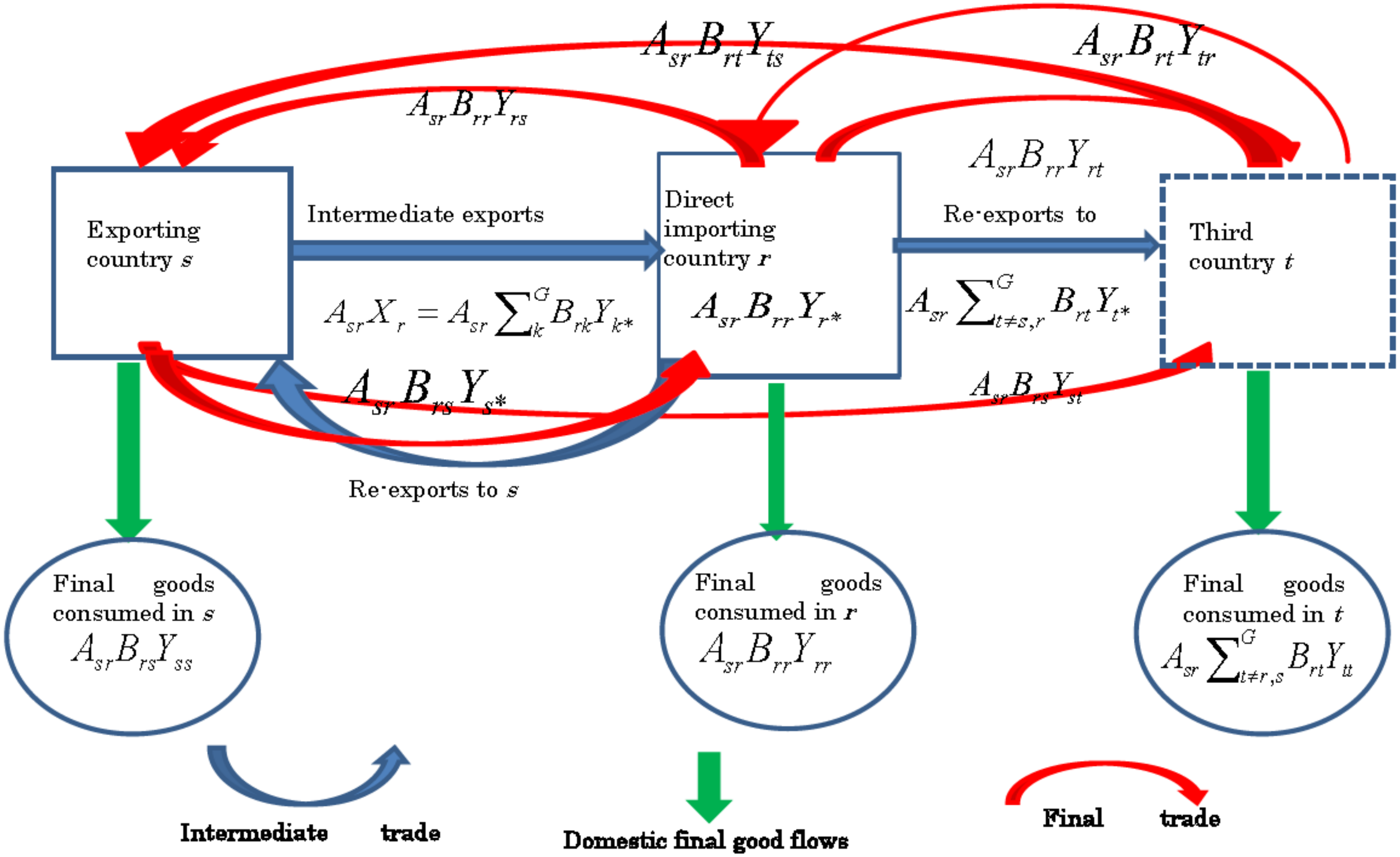
(A12)

This decomposition is intuitively illustrated by figure A1.

After laying out the idea of how bilateral gross intermediate trade flows are decomposed, we provide a detailed step by step proof in a 3-country setting to simplify notation and make the materials accessible to more readers. Inserting equations (A10) and (A12) into the left hand of equation (19) in the main text, which defines domestic emissions embodied in gross exports from country *s* to country *r* based on forward industrial linkages, we obtain

$$\begin{aligned}
&EEG\_F^{sr} = \hat{F}^{s} L^{ss} E^{sr} \\
&= \hat{F}^{s} L^{ss} Y^{sr} + \hat{F}^{s} \left[L^{ss} A^{sr} B^{rr} Y^{rr} + L^{ss} A^{sr} B^{rt} Y^{tr} + L^{ss} A^{sr} B^{rs} Y^{sr} \right] \\
&+ \hat{F}^{s} \left[L^{ss} A^{sr} B^{rr} Y^{rt} + L^{ss} A^{sr} B^{rt} Y^{tt} + L^{ss} A^{sr} B^{rs} Y^{st} \right] \\
&+ \hat{F}^{s} \left[VL^{ss} A^{sr} B^{rr} Y^{rs} + L^{ss} A^{sr} B^{rt} Y^{ts} + L^{ss} A^{sr} B^{rs} Y^{ss} \right]
\end{aligned} \tag{A13}$$

Figure A1. Accounting for gross bilateral intermediate trade flows between country s and country r



Source: improved from Wang, Wei and Zhu (2014) Learning about global value chains by looking beyond official trade data: Part 1. http://www.voxeu.org/article/learning-about-global-value-chains-looking-beyond-official-trade-data-part-1

The 1st term, $\hat{F}^{s} L^{ss}Y^{sr}$, represents emissions generated by each industry of country *s* embodied in its final goods exports to country *r*. The 2nd-4th terms (the 1st bracket) are emissions generated by each industry of country *s* embodied in its intermediate exports to country *r* that are driven by final demand in country *r*. The 5th-7th terms (the 2nd bracket) are emissions generated by each industry of country *s* embodied in its intermediate exports to country *r* that are driven by final demand in third countries (*t*). The 8th-10th terms (the 3rd bracket) are emissions generated by each industry of country *s* embodied in its intermediate exports to country *r* that ultimately return and are driven by final demand in country *s*.

Based on equation (17) in the main text, EEX_F^{sr}, embodied emissions in exports from country *s* to country *r* based on forward industrial linkage in a three country world can be expressed as

$$\begin{aligned}
EEX\_F^{sr} &= \hat{F}^{s} B^{ss}Y^{sr} + \hat{F}^{s} B^{sr}Y^{rr} + \hat{F}^{s} B^{st}Y^{tr} \\
&= \hat{F}^{s}\left[L^{ss}Y^{sr} + (B^{ss} - L^{ss})Y^{sr}\right] + \hat{F}^{s}\left[L^{ss}A^{sr}B^{rr}Y^{rr} + L^{ss}A^{st}B^{tr}Y^{rr}\right] \\
&+ \hat{F}^{s}\left[L^{ss}A^{sr}B^{rt}Y^{tr} + L^{ss}A^{st}B^{tt}Y^{tr}\right] = \hat{F}^{s} L^{ss}Y^{sr} + \hat{F}^{s}\left[L^{ss}A^{sr}B^{rs}Y^{sr} + L^{ss}A^{st}B^{ts}Y^{sr}\right] \\
&+ \hat{F}^{s}\left[L^{ss}A^{sr}B^{rr}Y^{rr} + L^{ss}A^{st}B^{tr}Y^{rr}\right] + \hat{F}^{s}\left[L^{ss}A^{sr}B^{rt}Y^{tr} + L^{ss}A^{st}B^{tt}Y^{tr}\right]
\end{aligned} \qquad \text{(A14)}$$

Rearranging equation (A14) gives

$$\begin{aligned}
EEX\_F^{sr} &= \hat{F}^{s} L^{ss}Y^{sr} + \hat{F}^{s}\left[L^{ss}A^{sr}B^{rr}Y^{rr} + L^{ss}A^{sr}B^{rt}Y^{tr} + L^{ss}A^{sr}B^{rs}Y^{sr}\right] \\
&+ \hat{F}^{s}\left[L^{ss}A^{st}B^{tr}Y^{rr} + L^{ss}A^{st}B^{tt}Y^{tr} + L^{ss}A^{st}B^{ts}Y^{sr}\right]
\end{aligned} \qquad \text{(A15)}$$

Therefore,

$$\begin{aligned}
EEG\_F^{sr} - VAX\_F^{sr} &= \hat{F}^{s} L^{ss}E^{sr} - \hat{F}^{s} B^{ss}Y^{sr} + \hat{F}^{s} B^{sr}Y^{rr} + \hat{F}^{s} B^{st}Y^{tr} \\
&= \hat{F}^{s}\left[L^{ss}A^{sr}B^{rr}Y^{rs} + L^{ss}A^{sr}B^{rt}Y^{ts} + L^{ss}A^{sr}B^{rs}Y^{ss}\right] \\
&+ \hat{F}^{s}\left[L^{ss}A^{sr}B^{rr}Y^{rt} + L^{ss}A^{sr}B^{rt}Y^{tt} + L^{ss}A^{sr}B^{rs}Y^{st}\right] \\
&- \hat{F}^{s}\left[L^{ss}A^{st}B^{tr}Y^{rr} + L^{ss}A^{st}B^{tt}Y^{tr} + L^{ss}A^{st}B^{ts}Y^{sr}\right]
\end{aligned} \qquad \text{(A16)}$$

The 1st bracket of equation (A16) is emissions by industry embodied in the intermediate exports of country *s* to country *r* that are ultimately returned to satisfy final demand at home, which is the same as equation (18) in the main text in a three country world. We call it REE_F^{sr}:

$$\begin{aligned}
REE\_F^{sr} &= \hat{F}^{s} L^{ss}A^{sr}B^{rr}Y^{rs} + \hat{F}^{s} L^{ss}A^{sr}B^{rt}Y^{ts} + \hat{F}^{s} L^{ss}A^{sr}B^{rs}Y^{ss} \\
&= \hat{F}^{s} L^{ss}A^{sr}\sum_{u}^{G} B^{ru}Y^{us}
\end{aligned} \qquad \text{(A17)}$$

The 2nd bracket in equation (A16) represents emissions by industry embodied in the intermediate exports from country *s* to country *r* that are driven by final demand in the third country (*t*). The 3rd bracket in equation (A16) represents emissions by industry embodied in the intermediate exports of country *s* to the third country (*t*) that are driven by final demand in country *r*. It is easy to understand that the 2nd and the 3rd brackets in equation (A16) are not equal to each other except very special cases. Therefore, neither EEG_F nor VLE based on forward linkage equals EEX_F + REE_F at bilateral and bilateral sector level.

However, summing up equation (A16) over all trade partners (i.e., countries *r* and *t* in the three country world), the terms in the 2nd bracket and the terms in the 3rd bracket will equal each other and cancel out:

$$\begin{aligned}
&\left[\hat{F}^{s} L^{ss} E^{sr} - EEX\_F^{sr}\right] + \left[\hat{F}^{s} L^{ss} E^{st} - EEX\_F^{st}\right] \\
&= REE\_F^{sr} + \hat{F}^{s}\left[L^{ss} A^{sr} B^{rr} Y^{rt} + L^{ss} A^{sr} B^{rt} Y^{tt} + L^{ss} A^{sr} B^{rs} Y^{st}\right] \\
&- \hat{F}^{s}\left[L^{ss} A^{st} B^{tr} Y^{rr} + L^{ss} A^{st} B^{tt} Y^{tr} + L^{ss} A^{st} B^{ts} Y^{sr}\right] \\
&+ REE\_F^{st} + \hat{F}^{s}\left[L^{ss} A^{st} B^{tr} Y^{rr} + L^{ss} A^{st} B^{tt} Y^{tr} + L^{ss} A^{st} B^{ts} Y^{sr}\right] \\
&- \hat{F}^{s}\left[L^{ss} A^{sr} B^{rr} Y^{rt} + L^{ss} A^{sr} B^{rt} Y^{tt} + L^{ss} A^{sr} B^{rs} Y^{st}\right] \\
&= REE\_F^{sr} + REE\_F^{st}
\end{aligned} \tag{A18}$$

Rearranging equation (A18) gives

$$\begin{aligned}
&EEG\_F^{sr} + EEG\_F^{st} = \hat{F}^{s} L^{ss} E^{sr} + \hat{F}^{s} L^{ss} E^{st} \\
&= \left[EEX\_F^{sr} + REE\_F^{sr}\right] + \left[EEX\_F^{st} + REE\_F^{st}\right]
\end{aligned} \tag{A19}$$

Therefore, EEG_F or VLE based on forward linkage are equal to EEX_F + REE_F at the country/sector and country aggregate levels. This proves that equation (20) in the main text holds.

A.3 Step by step proofs of Equations (25), (26) and (27) in the main text

Inserting equations (A10) and (A12) into the left hand side of equation (25) in the main text, which defines domestic emissions embodied in gross exports from country *s* to country *r* based on backward industrial linkages, we obtain the following equations for the three country world.

$$\begin{aligned}
&EEG\_B^{sr} = (F^{s} L^{ss})^{T} \# E^{sr} = (F^{s} L^{ss})^{T} \# Y^{sr} + (F^{s} L^{ss})^{T} \# (A^{sr} B^{rr} Y^{rr} + A^{sr} B^{rt} Y^{tr} + A^{sr} B^{rs} Y^{sr}) \\
&+ (F^{s} L^{ss})^{T} \# (A^{sr} B^{rt} Y^{tt} + A^{sr} B^{rr} Y^{rt} + A^{sr} B^{rs} Y^{st}) \\
&+ (F^{s} L^{ss})^{T} \# (A^{sr} B^{rr} Y^{rs} + A^{st} B^{rt} Y^{ts} + A^{sr} B^{rs} Y^{ss})
\end{aligned} \tag{A20}$$

This shows that EEG_B^{sr} can be decomposed into four parts: emissions embodied in final goods exports, emissions embodied in intermediate goods that are used to satisfy final demand in the direct importing country *r*, emissions embodied in intermediate exports returned to the exporting country *s*, and re-exported to third countries *t*. Emissions in these terms include emissions generated not only by the exporting sectors but also by other domestic sectors that contribute to the production of a particular sector's gross exports.

Based on equation (23) in the main text, EEX_B^{sr} can be expressed as

$$\begin{aligned} EEX\_B^{sr} &= (F^s B^{ss})^T \# Y^{sr} + (F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rr}) + (F^s L^{ss})^T \# (A^{sr} B^{rt} Y^{tr}) \\ &+ (F^s L^{ss})^T \# (A^{st} B^{tr} Y^{rr}) + (F^s L^{ss})^T \# (A^{st} B^{tt} Y^{tr}) \end{aligned} \tag{A21}$$

where

$$\begin{aligned} (F^s B^{ss})^T \# Y^{sr} &= (F^s L^{ss})^T \# Y^{sr} + (F^s B^{ss} - F^s L^{ss})^T \# Y^{sr} \\ &= (F^s L^{ss})^T \# Y^{sr} + (F^s L^{ss} A^{sr} B^{rs})^T \# Y^{sr} + (F^s L^{ss} A^{st} B^{ts})^T \# Y^{sr} \end{aligned} \tag{A22}$$

Inserting equation (A22) into equation (A21) we obtain

$$\begin{aligned} EEX\_B^{sr} &= (F^s L^{ss})^T \# Y^{sr} + (F^s L^{ss} A^{sr} B^{rs})^T \# Y^{sr} + (F^s L^{ss} A^{st} B^{ts})^T \# Y^{sr} \\ &+ (F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rr}) + (F^s L^{ss})^T \# (A^{st} B^{tt} Y^{tr}) \\ &+ (F^s L^{ss})^T \# (A^{st} B^{tr} Y^{rr}) + (F^s L^{ss})^T \# (A^{sr} B^{rt} Y^{tr}) \end{aligned} \tag{A23}$$

Therefore

$$\begin{aligned} &(F^s L^{ss})^T \# E^{sr} - EEX\_B^{sr} \\ &= (F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rs} + A^{sr} B^{rt} Y^{ts} + A^{sr} B^{rs} Y^{ss}) \\ &+ (F^s L^{ss})^T \# (A^{sr} B^{rt} Y^{tt} + A^{sr} B^{rr} Y^{rt} + A^{sr} B^{rs} Y^{st}) \\ &- [(F^s L^{ss})^T \# (A^{st} B^{tr} Y^{rr} + A^{st} B^{tt} Y^{tr}) + (F^s L^{ss} A^{st} B^{ts})^T \# Y^{sr}] \\ &+ [(F^s L^{ss})^T \# A^{sr} B^{rs} Y^{sr} - (F^s L^{ss} A^{sr} B^{rs})^T \# Y^{sr}] \end{aligned} \tag{A24}$$

The first term of equation (A24) represents the amount of emissions embodied in the sectoral exports from country *s* to country *r* that finally return home, and is exactly the same as equation (26) in the main text in a three country world:

$$REE\_B^{sr} = (F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rs}) + (F^s L^{ss})^T \# (A^{sr} B^{rt} Y^{ts}) + (F^s L^{ss})^T \# (A^{sr} B^{rs} Y^{ss}) \tag{A25}$$

The second term of equation (A24) represents emissions in the sectoral intermediate exports of country *s* to country *r* which are then re-exported to other countries (both countries *r* and *s*) to produce final products that are consumed in the third country *t*. The third term of equation (A24) represents emissions in the gross intermediate exports of country *s* to third country *t* to produce final product exports to country *r* or produce intermediate products exports to countries *r* or *s* for production of final goods and services consumed in country *r*. As we will show later, $(F^{s}L^{ss})^{T}\#A^{sr}B^{rs}Y^{sr}=(F^{s}L^{ss}A^{sr}B^{rs})^{T}\#Y^{sr}$ at the bilateral aggregate level but not at the bilateral/sector level.

Therefore

$$\begin{aligned}
&EEG\_B^{sr}-EEX\_B^{sr}-REE\_B^{sr}=(F^{s}L^{ss})^{T}\#(A^{sr}B^{rt}Y^{tt}+A^{sr}B^{rr}Y^{rt}+A^{sr}B^{rs}Y^{st})\\
&+[(F^{s}L^{ss})^{T}\#A^{sr}B^{rs}Y^{sr}-(F^{s}L^{ss}A^{sr}B^{rs})^{T}\#Y^{sr}]\\
&-[(F^{s}L^{ss})^{T}\#(A^{st}B^{tr}Y^{rr}+A^{st}B^{tt}Y^{tr})+(F^{s}L^{ss}A^{st}B^{ts})^{T}\#Y^{sr}]\neq 0
\end{aligned}\tag{A26}$$

It is obvious that the positive and negative terms in equation (A26) are not equal to each other except in very special cases. This indicates that EEG_B^{sr} and (EEX_B^{sr} +REE_ B^{sr}) cannot be equal each to other at the bilateral/sector level in general. At the bilateral aggregate level, summing (A26) over sectors, we obtain

$$\begin{aligned}
&uEEG\_B^{sr}-uEEX\_B^{sr}-uREE\_B^{sr}=u(F^{s}L^{ss})^{T}\#(A^{sr}B^{rt}Y^{tt}+A^{sr}B^{rr}Y^{rt}+A^{sr}B^{rs}Y^{st})\\
&-u(F^{s}L^{ss})^{T}\#(A^{st}B^{tr}Y^{rr}+A^{st}B^{tt}Y^{tr}+A^{st}B^{ts}Y^{sr})\\
&=F^{s}(L^{ss}A^{sr}B^{rt}Y^{tt}+L^{ss}A^{sr}B^{rr}Y^{rt}+L^{ss}A^{sr}B^{rs}Y^{st})\\
&-F^{s}(L^{ss}A^{st}B^{tr}Y^{rr}+L^{ss}A^{st}B^{tt}Y^{tr}+L^{ss}A^{st}B^{ts}Y^{sr})\neq 0
\end{aligned}\tag{A27}$$

The two terms in equation (A27) are still not equal each other in general. Therefore, the sum of $uEEX\_B^{sr}$ and $uREE\_B^{sr}$ does not equal $uEEG\_B^{sr}$ at the bilateral aggregate level.

Summing up equation (A27) over all trading partners *r* and *t*, the positive and negative terms will cancel out:

$$\begin{aligned}
&uEEG\_B^{sr}+uEEG\_B^{st}-u(EEX\_B^{sr}-REE\_B^{sr}-EEX\_B^{st}-REE\_B^{st})\\
&=F^{s}(L^{ss}A^{sr}B^{rt}Y^{tt}+L^{ss}A^{sr}B^{rr}Y^{rt}+L^{ss}A^{sr}B^{rs}Y^{st})\\
&-F^{s}(L^{ss}A^{st}B^{tr}Y^{rr}+L^{ss}A^{st}B^{tt}Y^{tr}+L^{ss}A^{st}B^{ts}Y^{sr})\\
&+F^{s}(L^{ss}A^{st}B^{tr}Y^{rr}+L^{ss}A^{st}B^{tt}Y^{tr}+L^{ss}A^{st}B^{ts}Y^{sr})\\
&-F^{s}(L^{ss}A^{sr}B^{rt}Y^{tt}+L^{ss}A^{sr}B^{rr}Y^{rt}+L^{ss}A^{sr}B^{rs}Y^{st})=0
\end{aligned}\tag{A28}$$

Therefore, equation (27) in the main text holds.

$$\sum_{r\neq s}^{G}uEEG\_B^{sr}=\sum_{r\neq s}^{G}(uEEX\_B^{sr}+uREE\_B^{sr})=\sum_{s\neq r}^{G}F^{s}L^{ss}E^{sr}$$

In a two-sector case,

$$
\begin{aligned}
&(F^{s}L^{ss})^{T}\#A^{sr}B^{rs}Y^{sr}-(F^{s}L^{ss}A^{sr}B^{rs})^{T}\#Y^{sr}\\
&=\begin{bmatrix} f_1^{s} & f_2^{s}\end{bmatrix}\begin{bmatrix} l_{11}^{ss} & l_{12}^{ss}\\ l_{21}^{ss} & l_{22}^{ss}\end{bmatrix}\#\begin{bmatrix} a_{11}^{sr} & a_{12}^{sr}\\ a_{12}^{sr} & a_{22}^{sr}\end{bmatrix}\begin{bmatrix} b_{11}^{rs} & b_{12}^{rs}\\ b_{21}^{rs} & b_{22}^{rs}\end{bmatrix}\begin{bmatrix} y_1^{sr}\\ y_2^{sr}\end{bmatrix}\\
&-\left\{\begin{bmatrix} f_1^{s} & f_2^{s}\end{bmatrix}\begin{bmatrix} l_{11}^{ss} & l_{12}^{ss}\\ l_{21}^{ss} & l_{22}^{ss}\end{bmatrix}\begin{bmatrix} a_{11}^{sr} & a_{12}^{sr}\\ a_{21}^{sr} & a_{22}^{sr}\end{bmatrix}\begin{bmatrix} b_{11}^{rs} & b_{12}^{rs}\\ b_{21}^{rs} & b_{22}^{rs}\end{bmatrix}\right\}\#\begin{bmatrix} y_1^{sr}\\ y_2^{sr}\end{bmatrix}\\
&=\begin{bmatrix} f_1^{s}l_{11}^{ss}+f_2^{s}l_{21}^{ss}\\ f_1^{s}l_{12}^{ss}+f_2^{s}l_{22}^{ss}\end{bmatrix}\#\begin{bmatrix} a_{11}^{sr}b_{11}^{rs}y_1^{sr}+a_{11}^{sr}b_{12}^{rs}y_2^{sr}+a_{12}^{sr}b_{21}^{rs}y_1^{sr}+a_{12}^{sr}b_{22}^{rs}y_2^{sr}\\ a_{21}^{sr}b_{11}^{rs}y_1^{sr}+a_{21}^{sr}b_{12}^{rs}y_2^{sr}+a_{22}^{sr}b_{21}^{rs}y_1^{sr}+a_{22}^{sr}b_{22}^{rs}y_2^{sr}\end{bmatrix}\\
&-\begin{bmatrix} f_1^{s}\sum_{i}^{2}l_{1i}^{ss}\sum_{j}^{2}a_{ij}^{sr}b_{j1}^{rs}+f_2^{s}\sum_{i}^{2}l_{2i}^{ss}\sum_{j}^{2}a_{ij}^{sr}b_{j1}^{rs}\\ f_1^{s}\sum_{i}^{2}l_{1i}^{ss}\sum_{j}^{2}a_{ij}^{sr}b_{j2}^{rs}+f_2^{s}\sum_{i}^{2}l_{2i}^{ss}\sum_{j}^{2}a_{ij}^{sr}b_{j2}^{rs}\end{bmatrix}\#\begin{bmatrix} y_1^{sr}\\ y_2^{sr}\end{bmatrix}\\
&=\begin{bmatrix} \sum_{i}^{2}f_i^{s}l_{i1}^{ss}\sum_{j}^{2}a_{1j}^{sr}\sum_{k}^{2}b_{jk}^{rs}y_k^{sr}\\ \sum_{i}^{2}f_i^{s}l_{i2}^{ss}\sum_{j}^{2}a_{2j}^{sr}\sum_{k}^{2}b_{jk}^{rs}y_k^{sr}\end{bmatrix}-\begin{bmatrix} \sum_{i}^{2}f_i^{s}\sum_{j}^{2}l_{ij}^{ss}\sum_{k}^{2}a_{jk}^{sr}b_{k1}^{rs}y_1^{sr}\\ \sum_{i}^{2}f_i^{s}\sum_{j}^{2}l_{ij}^{ss}\sum_{k}^{2}a_{jk}^{sr}b_{k2}^{rs}y_2^{sr}\end{bmatrix} \qquad \text{(A29)}\\
&=\begin{bmatrix} \sum_{i}^{2}f_i^{s}l_{i1}^{ss}\sum_{j}^{2}a_{1j}^{sr}b_{j2}^{rs}y_2^{sr}-\sum_{i}^{2}f_i^{s}l_{i2}^{ss}\sum_{j}^{2}a_{2j}^{sr}b_{j1}^{rs}y_1^{sr}\\ \sum_{i}^{2}f_i^{s}l_{i2}^{ss}\sum_{j}^{2}a_{2j}^{sr}b_{j1}^{rs}y_1^{sr}-\sum_{i}^{2}f_i^{s}l_{i1}^{ss}\sum_{j}^{2}a_{1j}^{sr}b_{j2}^{rs}y_2^{sr}\end{bmatrix}\neq\begin{bmatrix}0\\0\end{bmatrix}
\end{aligned}
$$

However,

$$
\begin{aligned}
&u(F^{s}L^{ss})^{T}\#A^{sr}B^{rs}Y^{sr}-u(F^{s}L^{ss}A^{sr}B^{rs})^{T}\#Y^{sr}\\
&=\begin{bmatrix}1 & 1\end{bmatrix}\begin{bmatrix} \sum_{i}^{2}f_i^{s}l_{i1}^{ss}\sum_{j}^{2}a_{1j}^{sr}b_{j2}^{rs}y_2^{sr}-\sum_{i}^{2}f_i^{s}l_{i2}^{ss}\sum_{j}^{2}a_{2j}^{sr}b_{j1}^{rs}y_1^{sr}\\ \sum_{i}^{2}f_i^{s}l_{i2}^{ss}\sum_{j}^{2}a_{2j}^{sr}b_{j1}^{rs}y_1^{sr}-\sum_{i}^{2}f_i^{s}l_{i1}^{ss}\sum_{j}^{2}a_{1j}^{sr}b_{j2}^{rs}y_2^{sr}\end{bmatrix}=0 \qquad \text{(A30)}
\end{aligned}
$$

Both elements in the last term in (A29) are not equal to zero in general. However, after aggregating over sectors, the two elements will cancel each other, as shown in equation (A30) Therefore, summing up equation (A26) over all trading partners *r* and *t*, but not over sectors, the positive and negative terms will not cancel out, as in equation (A27). This means $\sum_{r\neq s}^{G}EEG\_B^{sr}$ is also not equal to the sum of $\sum_{r\neq s}^{G}EEX\_B^{sr}$ and $\sum_{r\neq s}^{G}REE\_B^{sr}$ at the country-sector level.

Appendix B Additional Applications based on WIOD

B1 Who emits CO_2 emissions for whom

Table B1 shows how much some selected large countries' CO_2 emissions are induced by different sources of final demand through different routes of supply chains for both 1995 and 2009. From the upper part of Table B1 we see that China's total production-based CO_2 emissions experienced the largest increase (128%) from 2,723,066 kt in 1995 to 6,213,385 kt followed by India (108%) and the rest of the world (RoW, 37%)[1]. For all developed countries, their production-based CO_2 emissions decreased, especially for Germany which had the largest decrease of 12%.

Total production-based CO_2 emissions can be decomposed into 5 parts (referring to Figure 1) according to sources of final demand satisfied. The structure and changing pattern among these five final demand sources between 1995 and 2009 are shown in the middle and bottom parts of Table B1. Obviously, for all selected countries and for both years, the CO_2 emissions generated by the domestic production of goods and services that sell directly in the domestic market (EH_F) account for the majority of the total emissions, especially for countries with relatively large economic size. This is not surprising because most large countries' production is mainly for domestic use. The interesting thing is that the share of the remaining 4 sources shows a very different pattern across countries. For example, in both 1995 and 2009, the share of China's CO_2 emissions generated by its production of final goods exports (EEX_F1) is the largest when compared to the other selected countries. This implies that China's participation in GVCs is mainly through providing final goods exports and, naturally, relatively more CO_2 emissions are generated by this route. In contrast, Russia's CO_2 emissions generated by foreign final demand are mainly from providing intermediate goods exports (EEX_F2 + EEX_F3). This phenomenon clearly illustrates that a country's production-based CO_2 emissions depend not only on the energy efficiency of its production technology, but also on its position and participation in GVCs. Both Germany and UK have a

---

[1] The RoW here is not the rest of the selected countries shown in Table 1; it's the original country group of the RoW used in WIOD regarded as a group of all the other developing countries not covered by WIOD.

large portion of their production-based CO_2 emissions that are generated by the production of exports to meet foreign final demand, as China does, but with a much higher portion of such emissions generated by the production of intermediate exports. When looking at the changing pattern of the shares between 1995 and 2009 (the bottom right part of Table B1), for most countries except India, EH_F decreased, while other parts normally increased. This reflects the fact that most countries have been involved in GVCs and more of their emissions production is for satisfying final demands in foreign countries. In particular, the increase in the share for EEX_F2 is about 61% (from 9.1% to 14.7%) for China, and 63% (from 13.0% to 21.3%) for Germany. Since both countries have been the main supply hub of intermediate manufacturing goods in international trade, a relatively large portion of CO_2 emissions are naturally generated by this route. The share for EEX_F3 (emissions generated by the production of intermediates that re-exported to third countries) is lower than EEX_F1 and EEX_F2, while its rate of change for all countries is positive and very large. This clearly reflects the increasing complexity of GVCs, since more intermediate goods and services cross national borders more than once and are re-exported to third countries for further processing in the global production networks. In addition, the share for REE_F also experienced a dramatic increase for all selected developing countries, such as China (592%), India (294%) and the RoW (123%), although the absolute level of this share is extremely low. This implies that the final goods imported by China tend to embody more emissions generated by its own intermediate goods exports given its increasing presence in international production networks.

Table B1 CO2 emissions by sources of final demand (forward industrial-linkage-based decomposition, corresponding to Figure 1)

	1995						2009					
CO2 Emissions (KT)	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum
CHN	2,126,639	3,196	301,045	249,125	43,061	2,723,066	4,191,734	50,471	891,922	913,035	166,223	6,213,385
IND	607,263	165	39,284	65,961	8,154	720,827	1,266,226	1,356	95,723	116,290	22,214	1,501,809
JPN	874,562	3,068	43,965	90,214	12,458	1,024,267	753,151	3,223	47,700	124,446	25,217	953,737
USA	3,869,470	38,148	142,285	262,327	29,954	4,342,184	3,719,713	29,436	136,290	264,124	38,152	4,187,715
GBR	316,770	2,228	42,859	75,658	13,517	451,032	285,484	2,015	40,381	79,426	14,991	422,297
DEU	542,851	7,014	61,628	94,494	18,717	724,704	383,503	7,692	81,929	135,490	27,695	636,309
RUS	974,488	3,278	48,382	326,921	59,269	1,412,338	926,130	3,731	34,581	360,665	85,379	1,410,486
RoW	2,626,249	30,223	218,217	442,696	59,812	3,377,197	3,341,296	92,569	292,962	784,936	129,232	4,640,995
Share (%)	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum
CHN	78.1%	0.1%	11.1%	9.1%	1.6%	100.0%	67.5%	0.8%	14.4%	14.7%	2.7%	100.0%
IND	84.2%	0.0%	5.4%	9.2%	1.1%	100.0%	84.3%	0.1%	6.4%	7.7%	1.5%	100.0%
JPN	85.4%	0.3%	4.3%	8.8%	1.2%	100.0%	79.0%	0.3%	5.0%	13.0%	2.6%	100.0%
USA	89.1%	0.9%	3.3%	6.0%	0.7%	100.0%	88.8%	0.7%	3.3%	6.3%	0.9%	100.0%
GBR	70.2%	0.5%	9.5%	16.8%	3.0%	100.0%	67.6%	0.5%	9.6%	18.8%	3.5%	100.0%
DEU	74.9%	1.0%	8.5%	13.0%	2.6%	100.0%	60.3%	1.2%	12.9%	21.3%	4.4%	100.0%
RUS	69.0%	0.2%	3.4%	23.1%	4.2%	100.0%	65.7%	0.3%	2.5%	25.6%	6.1%	100.0%
RoW	77.8%	0.9%	6.5%	13.1%	1.8%	100.0%	72.0%	2.0%	6.3%	16.9%	2.8%	100.0%
Change rate between 1995 and 2009	Change rate of CO2 emisions between 1995 and 2009						Change rate of shares between 1995 and 2009					
	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum
CHN	97%	1479%	196%	266%	286%	128%	-14%	592%	30%	61%	69%	
IND	109%	722%	144%	76%	172%	108%	0%	294%	17%	-15%	31%	
JPN	-14%	5%	8%	38%	102%	-7%	-8%	13%	17%	48%	117%	
USA	-4%	-23%	-4%	1%	27%	-4%	0%	-20%	-1%	4%	32%	
GBR	-10%	-10%	-6%	5%	11%	-6%	-4%	-3%	1%	12%	18%	
DEU	-29%	10%	33%	43%	48%	-12%	-20%	25%	51%	63%	69%	
RUS	-5%	14%	-29%	10%	44%	0%	-5%	14%	-28%	10%	44%	
RoW	27%	206%	34%	77%	116%	37%	-7%	123%	-2%	29%	57%	

B2 CO_2 emissions generated in domestic and foreign segments of global supply chains

As shown in Figure 2, a country's CO_2 emissions can also be traced along global supply chains in terms of different types of energy source by using the backward industrial-linkage-based decomposition technique. Table B2 shows the decomposition results at the national level (sector aggregation) for selected countries for 1995 and 2009. In absolute terms, in 1995, the US's production of final products, no matter whether they are used domestically or internationally, generates massive amount of CO_2 emissions (4,423,852 kt). The US is followed by the RoW (3,382,085 kt) and China (2,513,050 kt). This depends both on a country's economic size and on its energy efficiency. In 2009, the situation changed dramatically: with a 125% increase compared to 1995, China becomes the largest emitter, followed by the RoW, the US and India. When looking at the share (the middle part of Table B3), we can see that CO_2 emissions generated in domestic segments of global supply chains accounts for the majority of total induced CO_2 emissions for all selected countries. This can be easily understood since, for most countries, their upstream supply chains are mainly located at home. However, the difference of the share across countries is still significant. For example, more than 20% of CO_2 emissions from Japan's, the UK and Germany's production of final products are generated in foreign segments of global supply chains in 1995. This clearly reflects at least two facts: one is that these countries' supply chains need more foreign intermediate inputs for producing final products, and the other is that much higher CO_2 emission intensity is located in foreign segments of their global supply chains than for the other selected developing countries.

The structure of energy use for producing final products in global supply chains varies across countries. China's and India's CO_2 emissions generated in their domestic supply chains are mainly from the use of coal (76.0% and 64.1% respectively in 1995). This depends not only on their relatively rich endowment of coal, but also on the higher CO_2 emission intensity in production processes using coal. This can also be indirectly confirmed by the fact that most of the CO_2 emissions generated in the foreign segment of Japan's supply chains were from coal in 2009, since most of its foreign upstream industries are located in China, which provides intermediate products mainly by using coal-based energy.

When looking at the pattern of structure changes between 1995 and 2009 (the bottom part of Table B2), some important features emerge. 1) For all selected countries, the share of CO_2 emissions generated in the domestic segment of their global supply chains declined, especially for China (-6.4%), England (-7.1%), Germany (-7.9%), and the RoW (-8.7%). On the other hand, the share of their foreign segments increased dramatically, especially for China (186%). Since countries tend to use more intermediate imports to make final goods, given the reduction in international trade costs, naturally more CO_2 emissions are generated in foreign segments of supply chains. 2) The share of coal, petroleum, and other energy-based CO_2 emissions generated in the domestic segment decreased, while natural gas and waste-based CO_2 emissions increased between 1995 and 2009. This reflects the fact that more countries are shifting to the usage of relatively low carbon intensity energy in the domestic part of their final goods production. Japan is the only exception, its coal-based CO_2 emissions in domestic segment increased 32.0 % from 1995 to 2009. This is mainly because Japan's energy efficiency is higher even if using coal to generate energy rather than thermal power generation; at the same time, it's cheaper to import coal from neighboring countries, like China which is a coal-rich country. 3) For almost all emission sources, their shares of CO_2 emissions in the foreign segment for all selected countries increased significantly between 1995 and 2009. In this regard, China's change is the most remarkable. This is mainly because China has been both the largest final goods assembler and a producer which also needs to import more components and intermediate inputs produced by foreign countries.

Table B2 CO2 emissions to produce a final goods and services in global supply chains (backward industrial-linkage-based decomposition, corresponding to Figure 2)

1995	CO2 emissions generated by domestic segment of GVC						CO2 emissions generated by foreign segment of GVC						Total	Change rate between 1995 and 2009
CO2 emissions (Kt)	Coal	Petroleum	Gas	Waste	Other	Subtotal	Coal	Petroleum	Gas	Waste	Other	Subtotal		
CHN	1,911,062	293,157	38,157	–	187,373	2,429,749	23,052	31,061	18,937	386	9,865	83,301	2,513,050	
IND	439,230	139,432	24,262	–	43,743	646,667	11,451	12,235	9,829	174	5,027	38,716	685,383	
JPN	236,609	484,494	125,142	2,703	71,315	920,263	95,738	96,867	53,407	664	29,841	276,517	1,196,780	
USA	1,641,832	1,421,481	731,322	35,302	198,759	4,028,696	120,695	139,960	85,996	1,332	47,173	395,156	4,423,852	
GBR	139,308	116,119	71,457	1,191	32,567	360,642	37,565	41,270	24,354	786	10,758	114,733	475,375	
DEU	307,303	197,880	87,580	8,777	6,097	607,637	84,962	73,667	62,218	2,475	27,492	250,814	858,451	
RUS	260,885	215,568	451,172	9,283	87,242	1,024,150	7,602	7,172	4,209	178	3,297	22,458	1,046,608	
RoW	614,637	1,393,462	639,832	3,633	210,533	2,862,097	162,491	232,758	77,264	2,158	45,317	519,988	3,382,085	
Share (%)	Coal	Petroleum	Gas	Waste	Other	Subtotal	Coal	Petroleum	Gas	Waste	Other	Subtotal	Total	
CHN	76.0%	11.7%	1.5%	0.0%	7.5%	96.7%	0.9%	1.2%	0.8%	0.0%	0.4%	3.3%	100.0%	
IND	64.1%	20.3%	3.5%	0.0%	6.4%	94.4%	1.7%	1.8%	1.4%	0.0%	0.7%	5.6%	100.0%	
JPN	19.8%	40.5%	10.5%	0.2%	6.0%	76.9%	8.0%	8.1%	4.5%	0.1%	2.5%	23.1%	100.0%	
USA	37.1%	32.1%	16.5%	0.8%	4.5%	91.1%	2.7%	3.2%	1.9%	0.0%	1.1%	8.9%	100.0%	
GBR	29.3%	24.4%	15.0%	0.3%	6.9%	75.9%	7.9%	8.7%	5.1%	0.2%	2.3%	24.1%	100.0%	
DEU	35.8%	23.1%	10.2%	1.0%	0.7%	70.8%	9.9%	8.6%	7.2%	0.3%	3.2%	29.2%	100.0%	
RUS	24.9%	20.6%	43.1%	0.9%	8.3%	97.9%	0.7%	0.7%	0.4%	0.0%	0.3%	2.1%	100.0%	
RoW	18.2%	41.2%	18.9%	0.1%	6.2%	84.6%	4.8%	6.9%	2.3%	0.1%	1.3%	15.4%	100.0%	
2009	CO2 emissions generated by domestic segment of GVC						CO2 emissions generated by foreign segment of GVC						Total	
CO2 emissions (Kt)	Coal	Petroleum	Gas	Waste	Other	Subtotal	Coal	Petroleum	Gas	Waste	Other	Subtotal		
CHN	4,098,564	552,773	142,473	0	326,088	5,119,898	161,716	170,108	146,806	3,421	54,990	537,041	5,656,939	125%
IND	952,788	244,857	79,460	0	85,728	1,362,833	57,762	36,723	32,685	510	13,875	141,555	1,504,388	119%
JPN	274,427	306,539	168,896	7,356	45,322	802,540	101,801	73,519	53,700	749	19,254	249,023	1,051,563	−12%
USA	1,632,018	1,259,978	798,603	53,355	126,083	3,870,037	238,903	160,596	136,688	2,075	55,471	593,733	4,463,770	1%
GBR	89,744	85,842	101,247	3,575	46,391	326,799	51,785	41,930	31,504	1,254	10,389	136,862	463,661	−2%
DEU	214,441	146,990	85,506	21,330	278	468,545	98,039	67,708	57,925	2,050	24,767	250,489	719,034	−16%
RUS	197,522	174,079	468,240	12,910	109,339	962,090	15,567	9,588	5,938	277	3,671	35,041	997,131	−5%
RoW	761,424	1,644,039	1,048,100	6,930	230,144	3,690,637	455,449	395,188	155,364	6,249	72,088	1,084,338	4,774,975	41%
Share (%)	Coal	Petroleum	Gas	Waste	Other	Subtotal	Coal	Petroleum	Gas	Waste	Other	Subtotal	Total	
CHN	72.5%	9.8%	2.5%	0.0%	5.8%	90.5%	2.9%	3.0%	2.6%	0.1%	1.0%	9.5%	100.0%	
IND	63.3%	16.3%	5.3%	0.0%	5.7%	90.6%	3.8%	2.4%	2.2%	0.0%	0.9%	9.4%	100.0%	
JPN	26.1%	29.2%	16.1%	0.7%	4.3%	76.3%	9.7%	7.0%	5.1%	0.1%	1.8%	23.7%	100.0%	
USA	36.6%	28.2%	17.9%	1.2%	2.8%	86.7%	5.4%	3.6%	3.1%	0.0%	1.2%	13.3%	100.0%	
GBR	19.4%	18.5%	21.8%	0.8%	10.0%	70.5%	11.2%	9.0%	6.8%	0.3%	2.2%	29.5%	100.0%	
DEU	29.8%	20.4%	11.9%	3.0%	0.0%	65.2%	13.6%	9.4%	8.1%	0.3%	3.4%	34.8%	100.0%	
RUS	19.8%	17.5%	47.0%	1.3%	11.0%	96.5%	1.6%	1.0%	0.6%	0.0%	0.4%	3.5%	100.0%	
RoW	15.9%	34.4%	21.9%	0.1%	4.8%	77.3%	9.5%	8.3%	3.3%	0.1%	1.5%	22.7%	100.0%	
Change rate of the share between 1995 and 2009 (%)	Coal	Petroleum	Gas	Waste	Other	Subtotal	Coal	Petroleum	Gas	Waste	Other	Subtotal	Total	
CHN	−4.7%	−16.2%	65.9%		−22.7%	−6.4%	211.6%	143.3%	244.4%	293.7%	147.6%	186.4%	0.0%	
IND	−1.2%	−20.0%	49.2%		−10.7%	−4.0%	129.8%	36.7%	51.5%	33.5%	25.7%	66.6%	0.0%	
JPN	32.0%	−28.0%	53.6%	209.7%	−27.7%	−0.7%	21.0%	−13.6%	14.4%	28.4%	−26.6%	2.5%	0.0%	
USA	−1.5%	−12.2%	8.2%	49.8%	−37.1%	−4.8%	96.2%	13.7%	57.5%	54.4%	16.5%	48.9%	0.0%	
GBR	−34.0%	−24.2%	45.3%	207.8%	46.0%	−7.1%	41.3%	4.2%	32.6%	63.6%	−1.0%	22.3%	0.0%	
DEU	−16.7%	−11.3%	16.6%	190.1%	−94.6%	−7.9%	37.8%	9.7%	11.2%	−1.1%	7.6%	19.2%	0.0%	
RUS	−20.5%	−15.2%	8.9%	46.0%	31.5%	−1.4%	114.9%	40.3%	48.1%	63.3%	16.9%	63.8%	0.0%	
RoW	−12.3%	−16.4%	16.0%	35.1%	−22.6%	−8.7%	98.5%	20.3%	42.4%	105.1%	12.7%	47.7%	0.0%	

B3 CO_2 emissions induced by the production of gross exports for selected countries

As shown in Figure 3, when applying the backward industrial-linkage-based decomposition technique, it will identify who emits CO_2 emissions for whom to what extent in the production of gross exports. Table B3 represents the decomposition results for selected countries at the national level for both 1995 and 2009. In absolute terms, the RoW's gross exports induce the largest amount of CO2 emissions (869,561 kt) in 1995 followed by China (717,838 kt) and the US (531,191 kt). The total CO_2 emissions can be separated into domestic and foreign parts. The majority of induced CO_2 emissions in producing exports were from the domestic side for all selected countries. However, if a country, in producing exports, has a relatively large part of the upstream production process outside its territory the share of foreign CO_2 emissions could be large, as for Germany (33%), England (24%) and Japan (20%). Both the domestic part and the foreign part can be further divided into 4 parts, each based on different supply chain routes and types of final consumer. Obviously, in 1995, 97% of CO_2 emissions embodied in China's gross exports is from the domestic side, in which 49% is for fulfilling final demand of trading partners who directly import goods from China; 35% is for fulfilling China's trading partners' demands for intermediate inputs in their production of domestically consumed goods and services; 13% is for fulfilling third countries' final demands by providing intermediate goods to China's trading partners for their production of exports to third countries; just 1% is for fulfilling China's own final demand by re-importing what has been exported. For most countries, except China, their domestic CO_2 emissions embodied in gross exports come mainly through trade in intermediate goods (parts 2, 3, 4). For Part 4, the figure for the US is larger than the other countries. This is mainly because the US re-imports a relatively large part of its own intermediate goods that have first been exported to global supply chains. For the foreign CO_2 emissions in producing gross exports, Germany shows the largest figure, in which parts 7 and 8 account for 17% and 15%, respectively. This indicates that 17% of the total CO_2 emissions embodied in Germany's gross exports is from third countries which export intermediate goods to Germany for Germany's further production of final goods for export to its trading partners. On the other hand, 15% of the total CO_2 emissions embodied in Germany's gross exports is from third countries that export intermediate goods to Germany, which uses these goods to produce further intermediate goods and exports to its trading partners for making domestically consumed final goods and services. Part 5 shows the CO_2 emissions induced in Germany's trading partner countries that provide intermediate goods to Germany for its production of final goods which are finally consumed in its trading partner countries. Part 6 shows the CO_2 emissions induced in Germany's trading partners which provide intermediate goods to Germany for further processing into intermediate exports, which are imported by Germany's trading partners for producing domestically used final goods and services. Together parts 5 and 6 account for just 1%, since this kind of feedback effect in international production networks is normally small.

In order to investigate the structural changes of gross-export-based CO_2 emissions between 1995 and 2009 across different routes, we calculate the rate of change for both the absolute CO_2 emissions figure and the corresponding share and show the results in the bottom two parts of Table B3. We see the following three features. 1) The induced CO_2 emissions in gross exports for all developing countries, such as China (262%), India (128%), and the RoW (85%), experienced a more rapid increase than developed countries. Given the decreasing CO_2 intensity, both for developing countries and developed countries from 1995 to 2009, the most important driving factor for this change should be the rapid increase of gross exports produced by developing countries. For England and the USA, there are only 1% and 5% increases, respectively. Japan and Germany also experienced 37% and 48% increases, respectively. Although both of them have been service oriented economies, they still play an important role as two large trade hubs of intermediate goods in global supply chains. 2) When looking at the change of share, we see that the share of domestic CO_2 emissions in producing exports decreased for all countries, while the share of foreign CO_2 emissions increased for most countries, except England. This indirectly reflects the fact that most countries are getting to use more intermediate imports to produce their exports. As a result, relatively more CO_2 emissions are induced internationally rather than domestically in producing exports. 3) Looking at the changing pattern for each part, we see that parts 3, 7 and 8 have a relatively large absolute share and also show a positive change of their shares between 1995 and 2009. Therefore, these parts can be considered the main leading factors that cause both the increase in the absolute emissions and the share of total gross-export-based CO_2 emissions for all countries. All these three parts are related to the third country effects in our decomposition. This implies that the increasing complexity of specific routes in global supply chains is often associated with a corresponding increase of CO_2 emissions.

Table B3 CO2 emissions in the production of gross exports (backward industrial-linkage-based decomposition, corresponding to Figure 3)

	1995										
CO2 emissions (KT)	Domestic CO2 emissions in producing exports					Foreign CO2 emissions in producing exports					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
CHN	301,045	214,501	77,685	3,196	596,427	1,241	940	12,392	6,839	21,411	617,838
IND	39,284	58,469	15,646	165	113,563	211	335	2,117	2,537	5,200	118,763
JPN	43,965	78,316	24,356	3,068	149,705	1,933	3,015	14,999	18,493	38,439	188,144
USA	142,285	228,543	63,738	38,148	472,714	3,176	4,034	25,195	26,072	58,477	531,191
GBR	42,859	61,174	28,001	2,228	134,262	1,784	1,973	20,562	17,855	42,174	176,436
DEU	61,628	76,173	37,038	7,014	181,853	2,924	2,586	45,228	40,108	90,846	272,700
RUS	48,382	260,126	126,064	3,278	437,850	85	286	993	3,679	5,043	442,893
RoW	218,217	382,331	120,177	30,223	750,948	5,530	5,760	50,908	56,416	118,613	869,561
Share (%)	Domestic CO2 emissions in producing exports					Foreign CO2 emissions in supplying imported inputs					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
CHN	49%	35%	13%	1%	97%	0%	0%	2%	1%	3%	100%
IND	33%	49%	13%	0%	96%	0%	0%	2%	2%	4%	100%
JPN	23%	42%	13%	2%	80%	1%	2%	8%	10%	20%	100%
USA	27%	43%	12%	7%	89%	1%	1%	5%	5%	11%	100%
GBR	24%	35%	16%	1%	76%	1%	1%	12%	10%	24%	100%
DEU	23%	28%	14%	3%	67%	1%	1%	17%	15%	33%	100%
RUS	11%	59%	28%	1%	99%	0%	0%	0%	1%	1%	100%
RoW	25%	44%	14%	3%	86%	1%	1%	6%	6%	14%	100%
	2009										
CO2 emissions (KT)	Domestic CO2 emissions in producing exports					Foreign CO2 emissions in producing exports					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
CHN	891,922	764,257	315,000	50,471	2,021,650	16,375	15,473	109,535	75,942	217,325	2,238,975
IND	95,723	92,687	45,817	1,356	235,583	2,634	2,029	21,564	9,298	35,524	271,107
JPN	47,700	98,451	51,212	3,223	200,586	3,276	7,268	19,022	27,921	57,487	258,073
USA	136,290	220,410	81,866	29,436	468,002	5,376	7,886	36,705	39,913	89,880	557,881
GBR	40,381	62,046	32,372	2,015	136,814	1,592	2,249	19,409	18,977	42,227	179,040
DEU	81,929	105,433	57,752	7,692	252,806	5,599	6,615	75,059	63,183	150,456	403,262
RUS	34,581	254,843	191,202	3,731	484,356	143	591	919	4,147	5,800	490,157
RoW	292,962	658,916	255,252	92,569	1,299,699	8,670	18,993	120,711	157,417	305,791	1,605,490
Share (%)	Domestic CO2 emissions in producing exports					Foreign CO2 emissions in supplying imported inputs					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
CHN	40%	34%	14%	2%	90%	1%	1%	5%	3%	10%	100%
IND	35%	34%	17%	1%	87%	1%	1%	8%	3%	13%	100%
JPN	18%	38%	20%	1%	78%	1%	3%	7%	11%	22%	100%
USA	24%	40%	15%	5%	84%	1%	1%	7%	7%	16%	100%
GBR	23%	35%	18%	1%	76%	1%	1%	11%	11%	24%	100%
DEU	20%	26%	14%	2%	63%	1%	2%	19%	16%	37%	100%
RUS	7%	52%	39%	1%	99%	0%	0%	0%	1%	1%	100%
RoW	18%	41%	16%	6%	81%	1%	1%	8%	10%	19%	100%
	Between 1995 and 2009										
Chage rate of CO2 emisions (%)	Domestic CO2 emissions in producing exports					Foreign CO2 emissions in supplying imported inputs					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
CHN	196%	256%	305%	1479%	239%	1220%	1547%	784%	1010%	915%	262%
IND	144%	59%	193%	722%	107%	1151%	506%	919%	266%	583%	128%
JPN	8%	26%	110%	5%	34%	69%	141%	27%	51%	50%	37%
USA	−4%	−4%	28%	−23%	−1%	69%	95%	46%	53%	54%	5%
GBR	−6%	1%	16%	−10%	2%	−11%	14%	−6%	6%	0%	1%
DEU	33%	38%	56%	10%	39%	91%	156%	66%	58%	66%	48%
RUS	−29%	−2%	52%	14%	11%	69%	106%	−7%	13%	15%	11%
RoW	34%	72%	112%	206%	73%	57%	230%	137%	179%	158%	85%
Chage rate of share (%)	Domestic CO2 emissions in producing exports					Foreign CO2 emissions in supplying imported inputs					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
CHN	−18%	−2%	12%	336%	−6%	264%	354%	144%	206%	180%	
IND	7%	−31%	28%	260%	−9%	448%	165%	346%	61%	199%	
JPN	−21%	−8%	53%	−23%	−2%	24%	76%	−8%	10%	9%	
USA	−9%	−8%	22%	−27%	−6%	61%	86%	39%	46%	46%	
GBR	−7%	0%	14%	−11%	0%	−12%	12%	−7%	5%	−1%	
DEU	−10%	−6%	5%	−26%	−6%	29%	73%	12%	7%	12%	
RUS	−35%	−11%	37%	3%	0%	53%	87%	−16%	2%	4%	
RoW	−27%	−7%	15%	66%	−6%	−15%	79%	28%	51%	40%	

B4 The potential environmental cost of value-added trade

As mentioned in the second section, following the proposed decomposition frameworks, both value-added and embodied emissions can be traced at the same time. When dividing the induced value added by induced CO_2 emissions, the potential environmental cost can be easily obtained. As an example, we apply this idea to the forward industrial-linkage-based decomposition (Figure 1) to show the relationship between trade in value added and trade in CO_2 emissions.

Table B4 The potential environmental cost of trade in value added (using forward industrial-linkage-based decomposition)

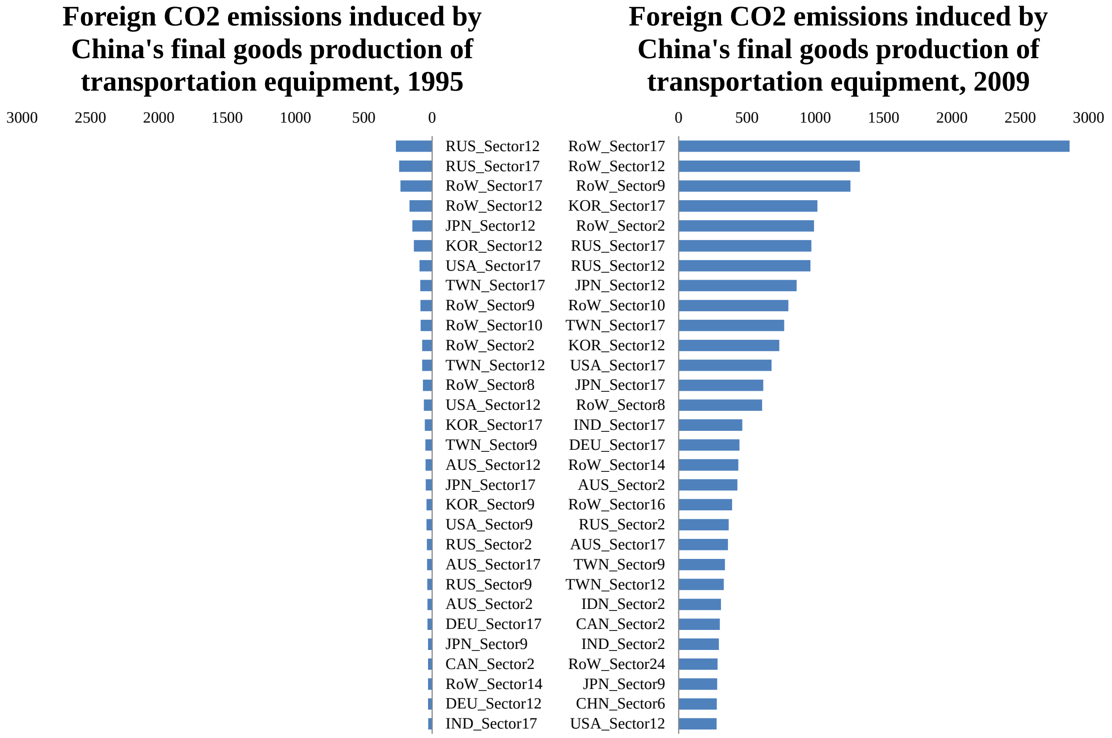
	1995					
CO2 emissions/value-added (KT/Million US$)	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum
CHN	3.6	4.6	3.9	4.6	4.3	3.7
IND	1.8	3.5	2.5	3.4	3.1	1.9
JPN	0.2	0.4	0.3	0.4	0.3	0.2
USA	0.6	0.7	0.7	0.7	0.7	0.6
GBR	0.4	0.6	0.5	0.6	0.6	0.4
DEU	0.3	0.4	0.3	0.4	0.4	0.3
RUS	3.9	5.9	4.2	6.0	6.4	4.4
RoW	1.0	1.5	1.4	1.4	1.5	1.1
	2009					
CO2 emissions/value-added (KT/Million US$)	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum
CHN	2.1	2.8	2.3	2.7	2.6	2.2
IND	1.6	2.7	1.8	2.2	2.3	1.6
JPN	0.2	0.4	0.3	0.4	0.3	0.2
USA	0.4	0.5	0.5	0.5	0.5	0.4
GBR	0.2	0.4	0.4	0.4	0.4	0.3
DEU	0.2	0.3	0.2	0.3	0.3	0.2
RUS	2.4	4.3	3.0	4.1	4.1	2.8
RoW	0.8	1.0	1.1	1.0	1.1	0.8
	between 1995 and 2009					
Change rate (%)	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	Sum
CHN	−41%	−40%	−40%	−42%	−40%	−40%
IND	−13%	−24%	−28%	−35%	−23%	−16%
JPN	−13%	−4%	0%	0%	2%	−8%
USA	−31%	−27%	−23%	−29%	−29%	−31%
GBR	−33%	−36%	−9%	−33%	−34%	−31%
DEU	−32%	−24%	−22%	−24%	−27%	−26%
RUS	−39%	−27%	−29%	−31%	−35%	−36%
RoW	−25%	−34%	−24%	−29%	−27%	−24%

The main results are shown in Table B4. In general, the environmental cost for producing domestic value added without international trade (referring to EH_F) for all countries is lower than that of producing domestic value added through international trade. This implies that the value-added gain by international trade may be through a high-carbon process, which indirectly reflects the fact of carbon leakage across countries due to trade. At the country level, Russia shows the highest environmental cost (4.4 kt/million US$) followed by China (3.7 kt/million US$) in 1995, which are, respectively 18.5 and 22.0, times more costly than Japan (0.2 kt/million US$). In 2009, for all countries, a cost decrease can be observed, especially for China (-40%) and Russia (-36%). Energy efficiency changes and emissions-related regulation conducted both domestically and internationally can be considered as the main driving factors of this cost decline. However, the situation regarding carbon leakage shows no significant change, since the environmental cost for getting value added by international trade is still higher than that for pure domestic production in 2009.

B5 CO_2 emissions generated in the foreign segment of global supply chains by specific products

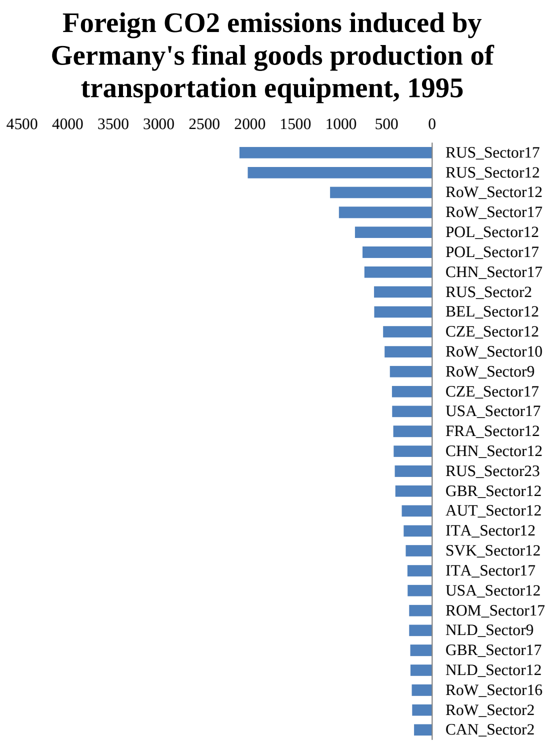
The backward industrial-linkage-based decomposition technique can help us trace the CO_2 emissions in supply chains at the detailed sector level for production of a specific final good in a particular country. As an example, Figure B1 shows the foreign sectors with the largest CO_2 emissions (top 30 out of 1435 sectors across all WIOD countries) in China's and Germany's Transportation Equipment supply chains for both 1995 and 2009. The major features can be summarized as follows. 1) The most intensive emitters of upstream countries in both countries' Transportation Equipment supply chains are from their neighboring countries. This is not surprising, since parts and components for producing cars follow the so-called just-in-time production system and trade costs across countries is one of the most important factors that affect the choice of production locations. It is, therefore, reasonable to build supply chains regionally rather than globally. 2) For both China and Germany, the most intensive foreign sector emitters in their Transportation Equipment supply chains are sectors 17 (Electricity, Gas and Water Supply), 12 (Basic Metals and Fabricated Metal), 9 (Chemicals and Chemical Products), and 2 (Mining and Quarrying). This depends on how close and strong the upstream sector links with the final product of transportation equipment, as well as the intensity of the CO_2 emissions arising from the production of parts and components directly and indirectly in the relevant upstream sectors. 3) Dramatic changes occur in the rankings of upstream countries and sectors during the 15 year sample period. This reflects the evolution of competitiveness not only in the quality and price of an upstream country or sector's intermediate goods in supply chains, but also on their energy efficiency. 4) The foreign segments in German car production are greener than those of China.

Figure B1 Foreign sectoral CO2 emissions (top 30 sectors) induced by a specific country's production of final goods (Transportation Equipment) in global supply chains

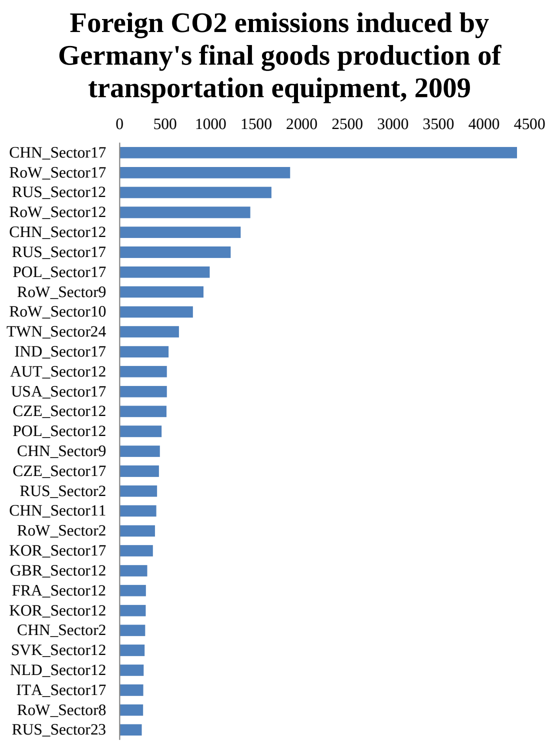


Foreign CO2 emissions induced by China's final goods production of transportation equipment, 1995

Foreign CO2 emissions induced by China's final goods production of transportation equipment, 2009



Foreign CO2 emissions induced by Germany's final goods production of transportation equipment, 1995

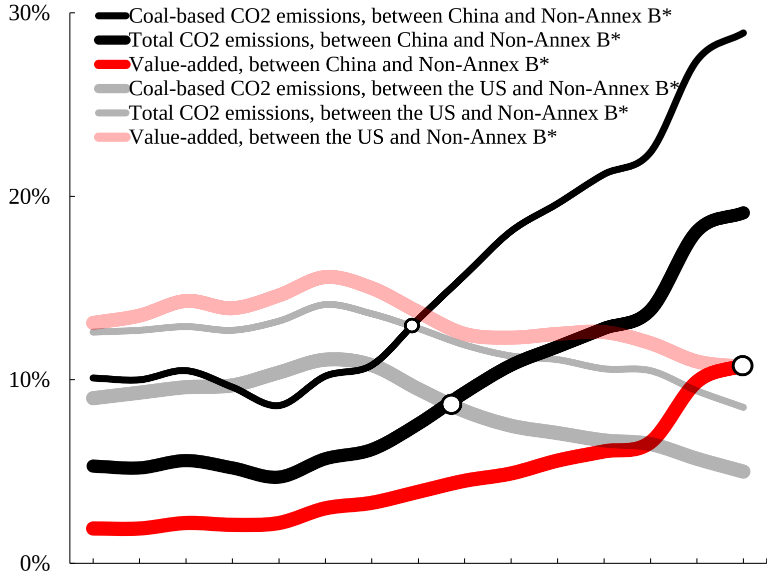


Foreign CO2 emissions induced by Germany's final goods production of transportation equipment, 2009

B6 Impacts of bilateral trade on CO2 emissions

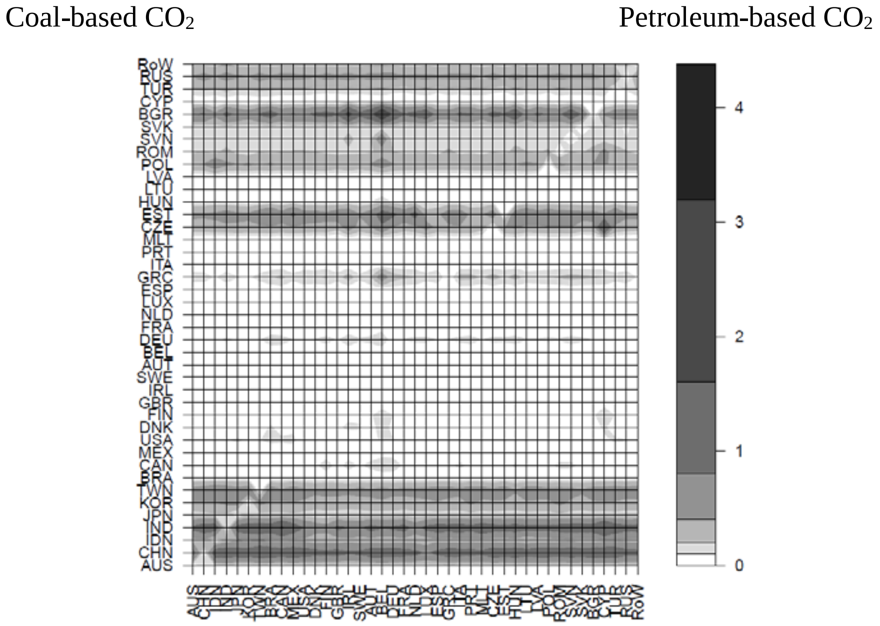
In order to elucidate how bilateral trade flows between China and Non-Annex B* countries impact on the global environment, the use of EEG_B measure should be a better choice. As we discussed in section 2, EEG_B is a production side concept, only concern the amount of emission generated by the production of a particular bilateral trade flow regardless where these traded products and services were consumed, so the emissions embodied in intermediate exports but final return to the source country are included. Figure XXX compares both the share of value-added and CO2 emission embodied in the bilateral trade between China and the US with Non-Annex B* countries as a share of GDP or emissions embodied in global trade respectively. It clearly shows that there are opposite trends for China-Non-Annex B* and US- Non-Annex B* bilateral flows. The embodied CO2 emissions share for China-Non-Annex B* countries experiences significant growth (from 5% to 19%), while the share of the US- Non-Annex B* countries has be in decline (from 13% to 9%). More remarkable difference can be observed in the share of coal based embodied CO2 emissions, which the share of China-Non-Annex B* countries increased from 10% to 29%, but the share of US- Non-Annex B* countries has decreased from 9% to 5% over the same period. This clearly indicates that the bilateral trade flows between China and Non-Annex B* countries became darker and darker over last two decades, increasingly became the major source of “carbon leakage” in the global production and trading system.

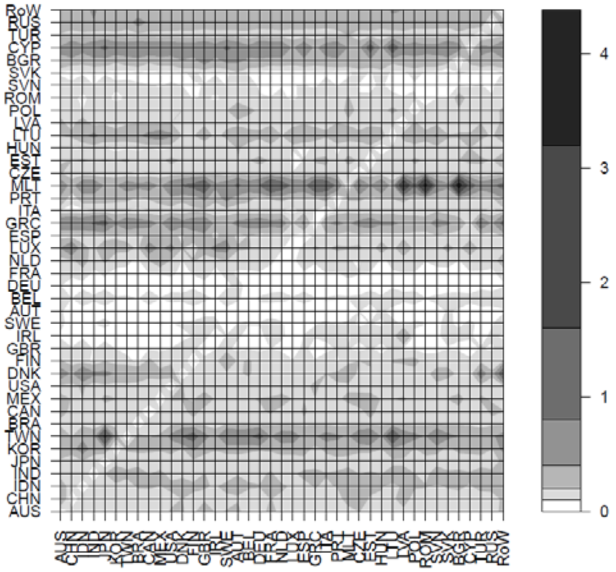
Figure B2 Embodied CO2 emissions in bilateral trade between China (US) and Non-Annex B* countries as a share of total embodied CO2 emissions in global trade



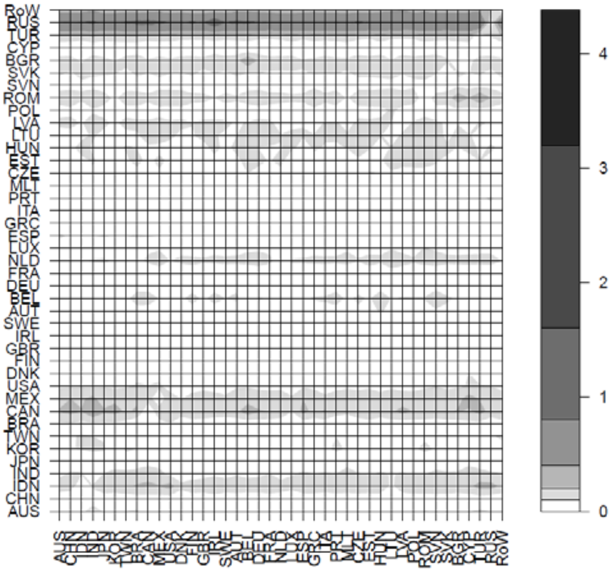
Note: Non-Annex B* excludes China.

Figure B3 The potential environmental costs at the bilateral level for different energy sources (2009, kt/million US$)





Natural gas-based CO_2 Other source-based CO_2



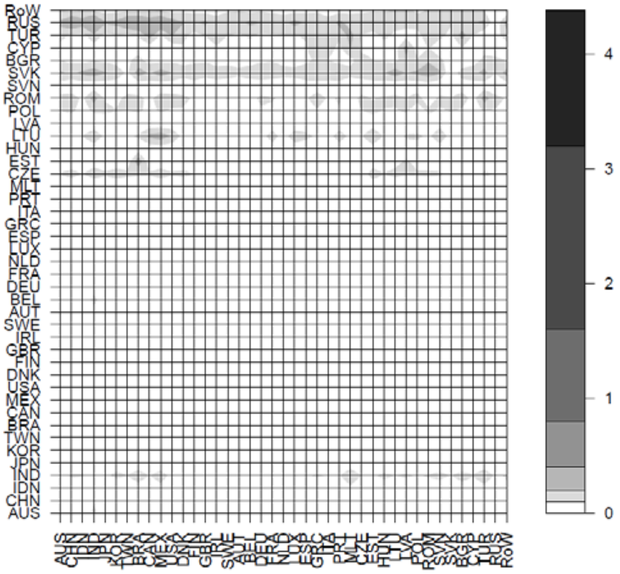

RoW
RUS
TUR
CYP
BGR
SVK
SVN
ROM
POL
LVA
LTU
HUN
EST
CZE
MLT
PRT
ITA
GRC
ESP
LUX
NLD
FRA
DEU
BEL
AUT
SWE
IRL
GBR
FIN
DNK
USA
MEX
CAN
BRA
TWN
KOR
JPN
IND
IDN
CHN
AUS
AUS
CHN
IDN
IND
JPN
KOR
TWN
BRA
CAN
MEX
USA
DNK
FIN
GBR
IRL
SWE
AUT
BEL
DEU
FRA
NLD
LUX
ESP
GRC
ITA
PRT
MLT
CZE
EST
HUN
LTU
LVA
POL
ROM
SVN
SVK
BGR
CYP
TUR
RUS
RoW
4
3
2
1
0

Table B5 The relationships among different measures of embodied CO_2 emissions and their applications

Level	Indicators Example	EEX	EEX_F	EEX_B	REE_F	REE_B	EEG_F	EEG_B	EEX_F+REE_F	EEX_B+REE_B
Bilateral-sector	(China→Japan, WIOD14)	38,634	867	39,206	31	1,395	880	39,427	898	40,601
Bilateral Aggregate	(China→Japan)	147,839	147,022	147,022	4,645	4,645	152,256	152,256	151,667	151,667
Country-Sector	(China→World, WIOD14)	557,698	12,463	557,698	428	19,804	12,891	574,614	12,891	577,502
Country Aggregate	（China→World）	1,971,179	1,971,179	1,971,179	50,471	50,471	2,021,650	2,021,650	2,021,650	2,021,650

Appendix C

C1 Sharing emission responsibility between producers and consumers along GVCs

A number of papers have discussed sharing responsibility between producers and consumers (Feng, 2003; Bastianoni et al., 2004; Rodrigues et al., 2006; Lenzen et al., 2007; Peters, 2008; Cadarso et al., 2012). However, two important problems remain unsolved. One is about how to correctly identify a country's pure self-responsibility of emissions along GVCs. Without a correct measure on this part, we even not able to know the amount of emission should be shared among related parties. This problem has been solved in our paper (see the first part in Equation 11). The pure self-responsibility of emissions is defined as the emissions generated in production of domestic consumed final goods and services without through any route of international trade (Part 1 in Figure 1). Another unsolved issue is about how to find an objective weight to share responsibility between producers and consumers. Lenzen et al. (2007) proposes to use value added as a weight, Cadarso et al., (2012) also follow this idea. However, there is an endogeneity problem due to value-added production is not independent to the emission level. In order to share responsibility more reasonably, we propose a new way to first measure the carbon leakage from both producers and consumer's perspectives based on the following hypothesis: if a country wants to keep its current final demand level in an autarky world, its emissions are defined as the emissions that this country just uses domestic production technology without importing any intermediate inputs to fulfill the same level of final demand as international trade exists. Compared this autarky emissions with both current production based and consumption based emissions, two indicators can be computed: production based carbon leakage and consumption based carbon leakage. These two indicators can be considered the carbon leakage that the country should take responsibility as a producer and a consumer respectively, thus the weight of shared responsibility can be obtained (for definition in mathematical terms and algorithm, one can refer to Appendix C2). Table 2 shows the results of shared emissions responsibility between producers and consumers for 41 economies in 2009. In the extreme case, that all responsibility goes to producers, China accounts for 29.8% followed by the RoW (19.2%), Russia (7.1%), the US (6.9%), Germany (3.7) and Korea (3.3%),. If all responsibility goes to consumers, the RoW accounts for 22.8% followed by the US (16.1%), China (7.9%), Germany (6.0%), and Japan (5.8%). Based on the shared responsibility we proposed, China should take 22.3%, the RoW 17.7%, the US 11.8%, Russia 7.1%, and Germany 4.4%.

Table C1 Shared responsibility of CO2 emissions along GVCs by country in 2009

2009 unit: Kt	Production based emissions	Consumption based emissions	Autarky Emissions	Production-based leakage	Consumption-based leakage	Production-based contribution to carbon leakage by country	Consumption-based contribution to carbon leakage by country	Share of Responsibility as producer	Share of Responsibility as consumer	Self-responsibility	Production based emissions should to be shared	Consumption based emissions should to be shared	Production based responsibility only	Consumption based responsibility only	Shared Production based responsibility	Shared Consumption based responsibility	Final responsibility by country	Final responsibility by country
	PP	PC	AE	CLP= PP−AE	CLC= PC−AE	CLPS	CLCS	∅= CLPS/ (CLPS+CLCS)	1−∅= CLCS/ (CLPS+CLCS)	SE	PPT=PP−SE	PCT=PC−SE	share of PPT by country	share of PCT by country	FSP	FSC	FS	share
AUS	364,325	414,091	311,892	52,433	102,199	1.1%	2.1%	33.9%	66.1%	277,544	86,781	136,547	1.3%	2.0%	24,576	75,370	99,946	1.5%
AUT	47,928	81,033	28,543	19,385	52,490	0.4%	1.1%	27.0%	73.0%	22,271	25,657	58,762	0.4%	0.9%	5,779	35,840	41,619	0.6%
BEL	91,053	116,888	48,898	42,155	67,990	0.8%	1.4%	38.3%	61.7%	34,114	56,939	82,774	0.8%	1.2%	18,200	42,672	60,872	0.9%
BGR	41,684	33,288	28,097	13,587	5,191	0.3%	0.1%	72.4%	27.6%	21,671	20,013	11,617	0.3%	0.2%	12,094	2,682	14,776	0.2%
BRA	251,288	306,481	218,098	33,190	88,383	0.7%	1.8%	27.3%	72.7%	207,891	43,397	98,590	0.6%	1.5%	9,895	59,859	69,754	1.0%
CAN	439,065	477,170	327,793	111,272	149,377	2.2%	3.0%	42.7%	57.3%	286,630	152,435	190,540	2.2%	2.8%	54,348	91,198	145,546	2.1%
CHN	6,213,385	4,725,895	4,429,743	1,783,642	296,152	35.9%	6.0%	85.8%	14.2%	4,191,734	2,021,651	534,161	29.8%	7.9%	1,447,984	63,524	1,511,508	22.3%
CYP	6,713	9,658	8,069	−1,356	1,589	0.0%	0.0%	−582.0%	682.0%	5,524	1,189	4,134	0.0%	0.1%	−5,779	23,546	17,767	0.3%
CZE	96,801	88,508	64,332	32,469	24,176	0.7%	0.5%	57.3%	42.7%	53,311	43,490	35,197	0.6%	0.5%	20,819	12,546	33,365	0.5%
DEU	636,309	793,786	453,403	182,906	340,383	3.7%	6.9%	35.0%	65.0%	383,503	252,806	410,283	3.7%	6.0%	73,798	222,885	296,682	4.4%
DNK	78,220	58,506	26,864	51,356	31,642	1.0%	0.6%	61.9%	38.1%	22,227	55,993	36,279	0.8%	0.5%	28,935	11,551	40,486	0.6%
ESP	230,728	313,198	188,144	42,584	125,054	0.9%	2.5%	25.4%	74.6%	162,766	67,962	150,432	1.0%	2.2%	14,418	93,721	108,139	1.6%
EST	14,245	11,215	11,001	3,244	214	0.1%	0.0%	93.8%	6.2%	7,475	6,770	3,740	0.1%	0.1%	5,304	193	5,498	0.1%
FIN	55,188	64,203	37,860	17,328	26,343	0.3%	0.5%	39.7%	60.3%	32,693	22,495	31,510	0.3%	0.5%	7,454	15,874	23,328	0.3%
FRA	260,360	434,683	206,686	53,674	227,997	1.1%	4.6%	19.1%	80.9%	175,568	84,792	259,115	1.2%	3.8%	13,494	175,166	188,660	2.8%
GBR	422,297	534,319	363,812	58,485	170,507	1.2%	3.4%	25.5%	74.5%	285,484	136,813	248,835	2.0%	3.7%	29,182	154,741	183,923	2.7%
GRC	93,776	124,461	91,941	1,835	32,520	0.0%	0.7%	5.3%	94.7%	78,452	15,324	46,009	0.2%	0.7%	684	36,373	37,056	0.5%
HUN	41,606	48,237	27,704	13,902	20,533	0.3%	0.4%	40.4%	59.6%	22,468	19,138	25,769	0.3%	0.4%	6,453	12,833	19,285	0.3%
IDN	331,193	323,133	257,954	73,239	65,179	1.5%	1.3%	52.9%	47.1%	245,345	85,848	77,788	1.3%	1.1%	37,936	30,591	68,527	1.0%
IND	1,501,808	1,458,813	1,330,284	171,524	128,529	3.5%	2.6%	57.2%	42.8%	1,266,226	235,582	192,587	3.5%	2.8%	112,471	68,897	181,368	2.7%
IRL	27,569	47,161	20,326	7,243	26,835	0.1%	0.5%	21.3%	78.7%	15,954	11,615	31,207	0.2%	0.5%	2,062	20,524	22,586	0.3%
ITA	329,336	459,195	268,285	61,051	190,910	1.2%	3.8%	24.2%	75.8%	237,923	91,413	221,272	1.3%	3.3%	18,499	140,021	158,519	2.3%
JPN	953,737	1,147,716	800,104	153,633	347,612	3.1%	7.0%	30.7%	69.3%	753,151	200,586	394,565	3.0%	5.8%	51,346	228,525	279,871	4.1%
KOR	532,878	469,954	341,918	190,960	128,036	3.8%	2.6%	59.9%	40.1%	310,646	222,232	159,308	3.3%	2.3%	111,105	53,402	164,507	2.4%
LTU	11,527	16,407	7,929	3,598	8,478	0.1%	0.2%	29.8%	70.2%	5,908	5,619	10,499	0.1%	0.2%	1,398	6,156	7,554	0.1%
LUX	3,039	7,169	1,461	1,578	5,708	0.0%	0.1%	21.7%	78.3%	1,197	1,842	5,972	0.0%	0.1%	333	3,907	4,240	0.1%
LVA	7,181	9,910	5,233	1,948	4,677	0.0%	0.1%	29.4%	70.6%	4,399	2,782	5,511	0.0%	0.1%	683	3,249	3,932	0.1%
MEX	351,280	384,635	303,997	47,283	80,638	1.0%	1.6%	37.0%	63.0%	278,366	72,914	106,269	1.1%	1.6%	22,508	55,947	78,455	1.2%
MLT	2,514	3,448	2,330	184	1,118	0.0%	0.0%	14.1%	85.9%	1,533	981	1,915	0.0%	0.0%	116	1,373	1,489	0.0%
NLD	166,194	179,325	86,684	79,510	92,641	1.6%	1.9%	46.2%	53.8%	69,900	96,294	109,425	1.4%	1.6%	37,143	49,179	86,322	1.3%
POL	275,037	251,284	213,241	61,796	38,043	1.2%	0.8%	61.9%	38.1%	187,194	87,843	64,090	1.3%	0.9%	45,408	20,395	65,804	1.0%
PRT	52,180	63,485	42,613	9,567	20,872	0.2%	0.4%	31.4%	68.6%	36,027	16,153	27,458	0.2%	0.4%	4,240	15,724	19,964	0.3%
ROM	76,798	82,187	63,099	13,699	19,088	0.3%	0.4%	41.8%	58.2%	56,019	20,779	26,168	0.3%	0.4%	7,251	12,723	19,974	0.3%
RUS	1,410,486	1,037,438	1,099,441	311,045	−62,003	6.3%	−1.2%	124.9%	−24.9%	926,130	484,356	111,308	7.1%	1.6%	505,227	−23,144	482,082	7.1%
SVK	33,179	34,703	19,685	13,494	15,018	0.3%	0.3%	47.3%	52.7%	14,598	18,581	20,105	0.3%	0.3%	7,344	8,844	16,188	0.2%
SVN	13,042	16,324	8,319	4,723	8,005	0.1%	0.2%	37.1%	62.9%	6,825	6,217	9,499	0.1%	0.1%	1,927	4,989	6,916	0.1%
SWE	47,351	74,119	28,143	19,208	45,976	0.4%	0.9%	29.5%	70.5%	21,842	25,509	52,277	0.4%	0.8%	6,278	30,794	37,072	0.5%
TUR	239,608	269,083	198,350	41,258	70,733	0.8%	1.4%	36.8%	63.2%	185,151	54,457	83,932	0.8%	1.2%	16,755	44,273	61,028	0.9%
TWN	290,360	198,033	150,726	139,634	47,307	2.8%	1.0%	74.7%	25.3%	129,888	160,472	68,145	2.4%	1.0%	100,105	14,402	114,507	1.7%
USA	4,187,715	4,812,099	3,958,044	229,671	854,055	4.6%	17.2%	21.2%	78.8%	3,719,713	468,002	1,092,386	6.9%	16.1%	82,833	718,974	801,807	11.8%
RoW	4,640,995	4,888,737	3,821,591	819,404	1,067,146	16.5%	21.5%	43.4%	56.6%	3,341,296	1,299,699	1,547,441	19.2%	22.8%	471,458	731,038	1,202,496	17.7%
Total	**24,869,978**	**24,869,978**	**19,902,637**	**4,967,341**	**4,967,341**	**100.0%**	**100.0%**	**50.0%**	**50.0%**	**0**	**6,783,422**	**6,783,422**	**100.0%**	**100.0%**	**3,412,064**	**3,371,358**	**6,783,422**	**100.0%**

C2 Method and algorithm for sharing emissions responsibility between producers and consumers along GVCs

In an autarky state, if a country wants to keep the current final demand level, its emissions are defined as

$$\mathrm{AE}^s = \mathrm{F}^s L^{ss} \sum_r Y^{rs}.$$

In other words, AE^s represents the emission level that country s just uses domestic production technique without any intermediate imports to produce goods and service for fulfilling the same final demand level as international trade exists. Compared this Autarky Emissions with both current production based and consumption based emission levels, it's easy to get two indicators: production based carbon leakage and consumption based carbon leakage as shown below.

$$CLP^s = PP^s - AE^s,$$

$$CLC^s = PC^s - AE^s.$$

Clearly, CLP^s can be considered the carbon leakage that country s should take responsibility as a producer; CLC^s the carbon leakage that country s should take responsibility as a consumer. Following this definition, the contribution level by country for both types of leakage can further be defined as

$$CLPS^s = CLP^s / \sum_s CLP^s,$$

$$CLCS^s = CLC^s / \sum_s CLC^s.$$

The above contribution levels are naturally can be used to define producers' and consumers' responsibility shares (weights) respectively as

$$\emptyset^s = CLPS^s/(CLPS^s + CLCS^s),$$

$$(1 - \emptyset^s) = CLCS^s/(CLPS^s + CLCS^s).$$

Removing the pure-self-responsibility based emissions (SE) from both production and consumption based emissions, the remained parts are the targets to be shared.

$$PPT^s = PP^s - SE^s,$$

$$PCT^s = PP^s - SE^s.$$

Following Peters (2008)'s idea, the shared responsibility is given as

$$FS = \sum_s FSP^s + \sum_s FSC^s$$

$$= \sum_s \emptyset^s \cdot PPT^s + \sum_s (1 - \emptyset^s) \cdot PCT^s.$$

It should be noted, that by definition,

$$\sum_s PP^s = \sum_s PC^s => \sum_s PPT^s = \sum_s PCT^s.$$

In the process of sharing responsibility with $\emptyset^s$, there is no guarantee in the first step that the shared responsibility

$$FS = \sum_s PPT^s \ or = \sum_s PCT^s.$$

Here, we use the following iterative algorithm to share responsibility step by step.

$$FS_{t=1} = \sum_s \emptyset^s \cdot PPT^s + \sum_s (1-\emptyset^s) \cdot PCT^s.$$

$$FS_{t=2} = FS_{t=1} + \sum_s \emptyset^s \cdot PPT^s_{t=1} + \sum_s (1-\emptyset^s) \cdot PCT^s_{t=1}$$

$$FS_{t=3} = FS_{t=2} + \sum_s \emptyset^s \cdot PPT^s_{t=2} + \sum_s (1-\emptyset^s) \cdot PCT^s_{t=2}$$

$$\ldots$$

$$FS_{t=n} = FS_{t=n-1} + \sum_s \emptyset^s \cdot PPT^s_{t=n-1} + \sum_s (1-\emptyset^s) \cdot PCT^s_{t=n-1}$$

$$PPT^s_t = (FS_t \ - \sum_s PPT^s) \frac{PPT^s}{\sum_s PPT^s}; \ PCT^s_t = (FS_t \ - \sum_s PCT^s) \frac{PCT^s}{\sum_s PCT^s}$$

Given $0 \leq \emptyset^s \leq 1$, we have

$$Min\{PPT^s_t, PCT^s_t\} \leq \emptyset^s \cdot PPT^s_t + (1-\emptyset^s) \cdot PCT^s_t \leq Max\{PPT^s_t, PCT^s_t\}.$$

This gives the sufficient condition for getting converged results at the end of the above process. Namely, when $n \rightarrow \infty$, $FS_{t=n} = \sum_s PPT^s = \sum_s PCT^s$.

Appendix D

WIOD country/region names

Code	Country Code	Name	EU 15	Annex B used
C1	AUS	Australia		✓
C2	AUT	Austria	✓	✓
C3	BEL	Belgium	✓	✓
C4	BGR	Bulgaria		✓
C5	BRA	Brazil		
C6	CAN	Canada		✓
C7	CHN	China		
C8	CYP	Cyprus		
C9	CZE	Czech Republic		✓
C10	DEU	Germany	✓	✓
C11	DNK	Denmark	✓	✓
C12	ESP	Spain	✓	✓
C13	EST	Estonia		✓
C14	FIN	Finland	✓	✓
C15	FRA	France	✓	✓
C16	GBR	United Kingdom	✓	✓
C17	GRC	Greece	✓	✓
C18	HUN	Hungary		✓
C19	IDN	Indonesia		
C20	IND	India		
C21	IRL	Ireland	✓	✓
C22	ITA	Italy	✓	✓
C23	JPN	Japan		✓
C24	KOR	South Korea		
C25	LTU	Lithuania		✓
C26	LUX	Luxembourg	✓	✓
C27	LVA	Latvia		✓
C28	MEX	Mexico		
C29	MLT	Malta		
C30	NLD	Netherlands	✓	✓
C31	POL	Poland		✓
C32	PRT	Portugal	✓	✓
C33	ROM	Romania		✓
C34	RUS	Russian Federation		✓
C35	SVK	Slovakia		✓
C36	SVN	Slovenia		✓
C37	SWE	Sweden	✓	✓
C38	TUR	Turkey		
C39	TWN	Taiwan		
C40	USA	United States		✓
C41	RoW	Rest of the World		

WIOD sector classification

Code	Description
S1	Agriculture, Hunting, Forestry and Fishing
S2	Mining and Quarrying
S3	Food, Beverages and Tobacco
S4	Textiles and Textile Products
S5	Leather, Leather and Footwear
S6	Wood and Products of Wood and Cork
S7	Pulp, Paper, Paper , Printing and Publishing
S8	Coke, Refined Petroleum and Nuclear Fuel
S9	Chemicals and Chemical Products
S10	Rubber and Plastics
S11	Other Non-Metallic Mineral
S12	Basic Metals and Fabricated Metal
S13	Machinery, Nec
S14	Electrical and Optical Equipment
S15	Transport Equipment
S16	Manufacturing, Nec; Recycling
S17	Electricity, Gas and Water Supply
S18	Construction
S19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel
S20	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles
S21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods
S22	Hotels and Restaurants
S23	Inland Transport
S24	Water Transport
S25	Air Transport
S26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
S27	Post and Telecommunications
S28	Financial Intermediation
S29	Real Estate Activities
S30	Renting of M&Eq and Other Business Activities
S31	Public Admin and Defence; Compulsory Social Security
S32	Education
S33	Health and Social Work
S34	Other Community, Social and Personal Services
S35	Private Households with Employed Persons

Chapter 2

Inter-regional CO_2 Emissions Transfer in China's Domestic Value Chains

Lin GUO[1], Jinjun XUE[2], Bo MENG[3]

Abstract: This paper aims to investigate the creation and distribution pattern of CO_2 emissions in China's domestic-interregional value chains. We borrow the idea presented in the recent innovative works by Meng, Peters and Wang (2014) and MRIO model to measure how regional CO_2 emissions are transferred and outsourced across China's domestic regions by various value chain routes from both upstream and downstream perspectives. The main findings of this study based on the downstream oriented decomposition of value chains: 1) For all regions, the CO_2 emissions generated by the production of local produced goods and services that sale directly at local market account for the majority of the total emissions. 2) The share of CO_2 emissions generated by the production of intermediate outflow absorbed by the direct "import" region contribute the largest share of CO_2 emissions generated by the products consumed in other regions. 3) The Electricity, gas and water supply, Metal products, and Non-metallic mineral products and the Chemicals and chemical products accounts for the majority of the regional production based CO_2 emissions both inflow and outflow in all regions. The main findings of this study based on the upstream oriented decomposition of value chains: 1) CO_2 emissions generated in inner-regional segment of domestic value chains accounts for the majority of total induced CO_2 emissions for all regions except the North Municipalities. 2) The share of extra-regional CO_2 emissions in the North Municipalities, South Coast region and East

Coast region for producing outflows are larger than other regions. 3) The majority of induced CO_2 emissions in producing inter-regional exports come from the inner-regional side for all regions except the North Municipalities. 4) The environmental cost of value-added outflows for North East region, North Coast region, Central region, North West region and South West region are relatively higher than other regions. The cost decrease can be found for almost all regions except North West region.

Keywords: Domestic value chains, CO_2 emissions, region, carbon intensity

1: Lin GUO, Assistant Professor, School of International Trade and Economics, UIBE, China

2: Jinjun XUE, Professor, School of Economics, Nagoya University, Japan

3: Bo MENG, Research Fellow, IDE-JETRO, Japan

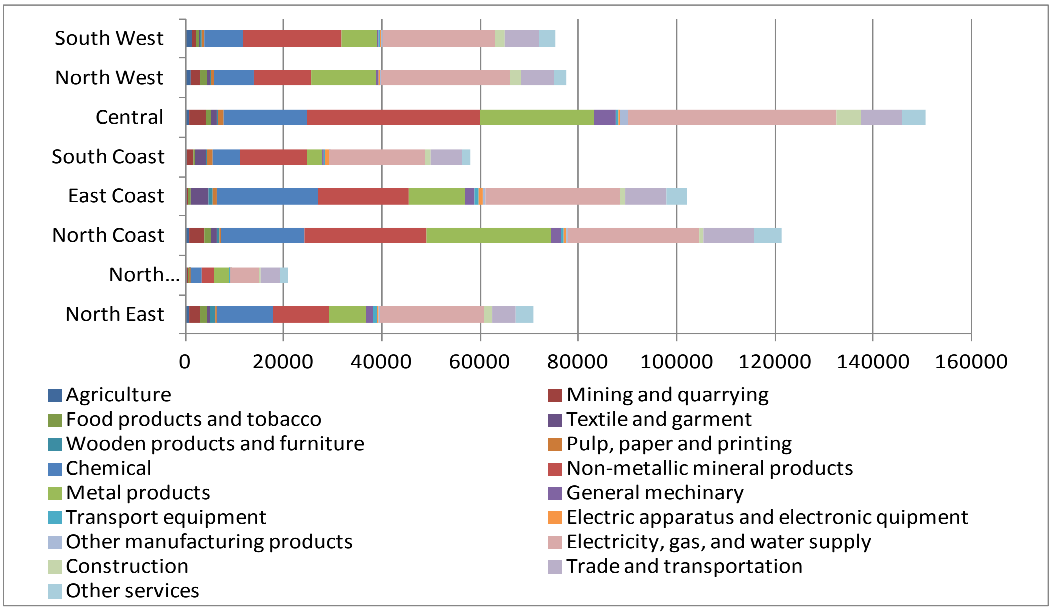
1. Introduction

In recent years, with high frequency of disastrous weather, climate change and green house gas emissions issues receive strong concerns from the world. As the largest developing country, China’s carbon dioxide (CO_2) emission increases rapidly (Auffhammer and Carson, 2008), which is fundamentally determined by the current economic development stage, large population and industry structure, though the per capita CO_2 emission is far below the average level of developed countries. In order to meet the demand of energy-saving and emission reduction, and respond to the call of international community for controlling greenhouse gas emissions, the Chinese government made a commitment before the 2009 U.N. Climate Change Conference in Copenhagen that by 2020, China’s CO_2 emission intensity would drop 40–45% on the basis of emissions in 2005. The goal will be brought into national economic and social development planning as a binding target, and the central government will formulate relative regulation of measuring, checking and statistics. Rapid urbanization, huge population pressure and large numbers of low efficiency but high energy-consuming industries determine that it requires great efforts to achieve the target.

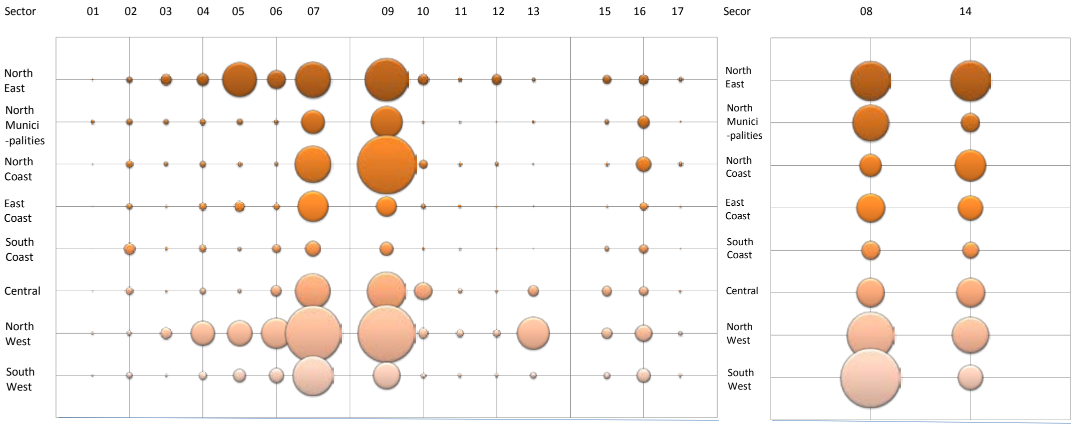
Several factors influence CO_2 emissions of a country, such as economic development, energy consumption structure, energy intensity and population (e.g., Ang, 1999; Roca and Alcantara, 2001; Shi, 2003; Lin etal., 2006; Zhou and Ang, 2008; Zhang et al., 2009; Sharma, 2011). Economic development is one of the most important factors. A number of studies analyzed the relationship between CO_2 emission and economic growth, see Grossman and Krueger (1995), Sun (1999), Auffhammer and Carson (2008), Jalil and Mahmud (2009), Chang (2010), Narayan and Narayan (2010). The situation that China faces is different with developed countries. Developed countries have already completed the process of urbanization and industrialization, but developing countries like China still have a long way to go. Zhang et al. (2009) analyzed the nature of the factors that influence the changes in energy-related CO_2 emission and CO_2 emission intensity during 1991–2006 in China, using complete decomposition approach. The results showed that energy intensity effect and economic activity effect are the dominant contributors to the change in CO_2 emission and CO2 emission intensity, but economic structure and CO_2 emission coefficient effects contribute little. Wang and Watson (2010) presented some general results of scenarios that had been developed to investigate how China might continue to develop within a cumulative carbon emissions budget. The results show how changes in the key sectors of the Chinese economy could enable China to follow different low carbon development pathways with cumulative emissions constraint. A certain speed of urbanization level raising and national economy growing are needed to deal with the population enlarging, living level improving and employment issues. So China's economic development and CO_2 emission control should be well balanced.

China's energy saving and emission reduction goals are usually decomposed into sub-goals and assigned to each province. However, huge differences among provinces on the economic development and energy structure make the difficulty and cost of carbon reduction different. Literatures on the characteristics of China's regional CO_2 emissions, the spatial distribution and the relationship between economic growth and carbon emission are relatively limited. Liang, et al. (2007) separated China into eight economic regions, used a multi-regional input–output (IO) model for energy requirements and CO_2 emissions in China to perform scenario and sensitivity analysis for each region in the years 2010 and 2020. Results showed that up to year 2020, improvement in energy end-use efficiency for each region could generate intra-regional energy savings. At the national level, the effectiveness of inter-regional energy transfers, and efficiency improvements in Central and Northwest regions should be accelerated as much as possible. Zhu et al. (2005) described the development of China's power industry, which is the largest contributor to CO_2 emissions, environmental influences and potential benefits of regional power grid interconnections in China. Feng et al. (2009) analyzed how population, affluence and emission intensity contributed to the growth of CO_2 emissions in five regions of China. The results showed that technological improvements have not been able to fully compensate for the increase in emissions due to population growth and increasing wealth. Developing countries like China needed to ensure that people's lifestyles are changing towards more sustainable ways of living. Liu et al. (2010) analyzed China's carbon emission changes during 1997–2007 for 30 domestic provinces. They identified the most important regions that cause higher CO_2 emissions from end-use energy consumption and emphasized that the decline in energy intensity has the greatest impact on CO_2 emissions. Meng et al. (2011) analyzed the characteristics of China's regional CO_2 emissions, the effects of economic growth and energy intensity using panel data from 1997 to 2009. Wang and Shi (2012) used an IO-based carbon footprint model to analyze China's provincial carbon footprint and inter-provincial transfer.

Most studies undertaken at the regional level of China focus on measuring energy and CO_2 emission intensities, influencing factors in CO_2 emissions change, and the embodied CO_2 emission in trade. Using the traditional analysis in previous studies, we can only get the information as shown in Figure 1. Namely, the chemical, non-metallic mineral products, metal products and electricity, gas, and water supply are the main contributors of carbon emissions in all regions. Also, we can find that these sectors have much higher carbon intensity than other sectors, especially in the island regions (Northwest, Southwest, Central and Northeast regions). However, this information is not enough for policy making. Obviously, deep insight on value chains is needed. Thus, a consistent and well defined accounting system is required, which can provide proper measurements to trace emission along each stage and from different perspectives of the Domestic Value Chains (DVCs). In order to build such an unified accounting framework, the existing efforts (Ahmad and Wyckoff, 2003; Lenzen et al., 2004; Peters and Hertwich, 2004; Peters, 2008; Peters and Hertwich, 2008a,b among others) on the measurement of embodied emissions in trade based on multi-regional Input-Output (IO) models provide a good starting point. However, most of these previous efforts focuses on measuring embodied emission at country aggregate level, often fail to provide both industry/product and bilateral level solution for capturing the embodied emissions in trade through both upstream and downstream supply chains. Meanwhile, Leontief's original method does not provide a way to decompose gross intermediate trade flows across regions according to their final absorption and falls to trace emissions generated by a region's gross outflows source structure based on backward industrial linkage. To do this, we borrow the idea presented in the recent innovative works by Meng, Peters and Wang (2014). They integrate two lines of research: trade in value-added/gross trade accounting (Koopman, Wang and Wei, AER, 2014; and Wang et al., 2014) and embodied emission trade/emission inventory accounting into a unified conceptual framework for the first time in the literature. This allows both value-added and emissions to be systematically traced at the country, sector, and bilateral levels thus the potential environmental cost (emission with per unit of value-added created) at each stage along Global Value Chains can be estimated. Proposed new measures (some of them are new compared to the existing literatures) clearly distinguish emissions of self-responsibility (emissions for domestic final demands without through international trade) and shared responsibility (emission through international trade) between producer and consumer located in different territories. In this chapter, we apply this idea to the Chinese domestic inter-regional value chains.



CO$_2$ emissions by sector and by region



Carbon intensity by sector and by region

Figure 1 CO_2 emissions and carbon intensity by sector and by region (2010)

Our study differs from the previous studies in the way that is able to address the following questions: 1) how much emission generated by a region's is for its own, its downstream region or sector's consumption via different DVCs routes? 2) How a region's production of a specific final good or service effects on its own and its upstream region or sector's emissions? 3) Who produces emissions for whom by what route along DVCs in the production of gross outflows? 4) How many emissions have been generated to create one unit GDP along various DVC routes?

The paper is organized as follows: Section 2 introduces the decomposition method used in this study; section 3 analyses the empirical decomposition results; section 4 provides our policy implications based on the empirical results, finally, we come to the conclusions in section 5.

2. Methodology

2.1 Decomposition by standard Leontief method

All the estimation and decomposition methods in the embedded emissions literatures are rooted in Leontief (1936). His work demonstrated that the amount and type of intermediate inputs needed in the production of one unit of output can be estimated based on the input-output (IO) structure.

To better understand how the Leontief method works in the multiregional IO model, let us assume a two-region model, in which each region produces goods in N differentiated tradable industries. Goods in each sector can be consumed directly or used as intermediate inputs, and each region exports both intermediate and final goods to the other region. Then the estimation and decomposition of region/sector level emissions production can be expressed as follows:

$$X^s = A^{ss}X^s + Y^{ss} + A^{sr}X^r + Y^{sr}\ r, s = 1{,}2 \qquad (1)$$

Where X^s and X^r are the N×1 gross output vectors of region *s* and region *r* respectively, Y^{ss} is the N×1 final demand vector for region *s*' final demand and Y^{sr} is the N×1 final demand vector that gives demand in region *r* of final goods produced in region *s*. Both A^{ss} and A^{sr} are the N×N IO coefficient matrix, $A^{ss}X^s$ denotes the goods produced in region *s* for region *s'* intermediate inputs, while $A^{sr}X^r$ represents the intermediate use in region *r* of goods produced in region *s*. Thus, all gross output produced by region *s* must be used as either an intermediate good or a final good within region *s* or outflow to region *r*.

The two-region production and interregional trade system can be written as a inter-region IO (IRIO) model in block matrix notation in equation (2).

$$\begin{aligned}\begin{bmatrix} X^s \\ X^r \end{bmatrix} &= \begin{bmatrix} A^{ss} & A^{sr} \\ A^{rs} & A^{rr} \end{bmatrix}\begin{bmatrix} X^s \\ X^r \end{bmatrix} + \begin{bmatrix} Y^{ss}+Y^{sr} \\ Y^{rs}+Y^{rr} \end{bmatrix} \\ &= \begin{bmatrix} 1-A^{ss} & -A^{sr} \\ -A^{rs} & 1-A^{rr} \end{bmatrix}^{-1}\begin{bmatrix} Y^{ss}+Y^{sr} \\ Y^{rs}+Y^{rr} \end{bmatrix} = \begin{bmatrix} B^{ss} & B^{sr} \\ B^{rs} & B^{rr} \end{bmatrix}\begin{bmatrix} Y^s \\ Y^r \end{bmatrix}\end{aligned} \qquad (2)$$

where B^{sr} denotes the N×N block matrix, commonly known as a Leontief inverse, which is the total requirement matrix that gives the amount of gross output in producing region *s* required for a one-unit increase in final demand in region *r*. B^{sr} is also the N×N total requirement matrix that denotes the amount of gross output in region *s* induced by a one-unit increase in final demand in region *s*. Y^s is an N×1 vector that gives global use of *s*' final goods, including domestic final goods sales Y^{ss} and final goods outflow Y^{sr}. Similarly, Y^r repesents an N×1 vector that gives global use of *r* final goods, including domestic final goods sales Y^{rr} and final goods outflow Y^{rs}

Define direct CO2 emissions intensity as $f_j^c \equiv p_j^c / x_j^c$ for c=s,r, j=1,2. Then the estimation and decomposition of country/sector level emissions production can be expressed as follows:

$$\hat{F}\,B\hat{Y} = \begin{bmatrix} f_1^s & 0 & 0 & 0 \\ 0 & f_2^s & 0 & 0 \\ 0 & 0 & f_1^r & 0 \\ 0 & 0 & 0 & f_2^r \end{bmatrix} \begin{bmatrix} b_{11}^{ss} & b_{12}^{ss} & b_{11}^{sr} & b_{12}^{sr} \\ b_{21}^{ss} & b_{22}^{ss} & b_{21}^{sr} & b_{22}^{sr} \\ b_{11}^{rs} & b_{12}^{rs} & b_{11}^{rr} & b_{12}^{rr} \\ b_{21}^{rs} & b_{22}^{rs} & b_{21}^{rr} & b_{22}^{rr} \end{bmatrix} \begin{bmatrix} y_1^{ss}+y_1^{sr} & 0 & 0 & 0 \\ 0 & y_2^{ss}+y_2^{sr} & 0 & 0 \\ 0 & 0 & y_1^{rs}+y_1^{rr} & 0 \\ 0 & 0 & 0 & y_2^{rs}+y_2^{rr} \end{bmatrix} \qquad (3)$$

$$= \begin{bmatrix} f_1^s b_{11}^{ss}(y_1^{ss}+y_1^{sr}) & f_1^s b_{12}^{ss}(y_2^{ss}+y_2^{sr}) & f_1^s b_{11}^{sr}(y_1^{rs}+y_1^{rr}) & f_1^s b_{12}^{sr}(y_2^{rs}+y_2^{rr}) \\ f_2^s b_{21}^{ss}(y_1^{ss}+y_1^{sr}) & f_2^s b_{22}^{ss}(y_2^{ss}+y_2^{sr}) & f_2^s b_{21}^{sr}(y_1^{rs}+y_1^{rr}) & f_2^s b_{22}^{sr}(y_2^{rs}+y_2^{rr}) \\ f_1^r b_{11}^{rs}(y_1^{ss}+y_1^{sr}) & f_1^r b_{12}^{rs}(y_2^{ss}+y_2^{sr}) & f_1^r b_{11}^{rr}(y_1^{rs}+y_1^{rr}) & f_1^r b_{12}^{rr}(y_2^{rs}+y_2^{rr}) \\ f_2^r b_{21}^{rs}(y_1^{ss}+y_1^{sr}) & f_2^r b_{22}^{rs}(y_2^{ss}+y_2^{sr}) & f_2^r b_{21}^{rr}(y_1^{rs}+y_1^{rr}) & f_2^r b_{22}^{rr}(y_2^{rs}+y_2^{rr}) \end{bmatrix}$$

Where y_i^{sr} is final goods produced by the ist sector in region *s* for consumption in region *r* (i,j =1,2). b_{11}^{ss} is the total requirement coefficient that gives the total amount of the gross output of the 1st sector in region *s* needed to produce an extra unit of the 1st sector's final good in region *s* (which is for consumption in both region *s* and region *r*). Other coefficients have similar economic interpretations.

This matrix gives the estimates of sector and region sources of emissions in each region's final goods production. Each element in the matrix represents emissions from a source industry of a source region directly or indirectly generated in the production of final goods (consumed in both the source region and the other region) in the source region.

Looking at the matrix along the row yields the distribution of emissions created from one region/sector across all regions/sectors. For example, the first element of the first row, $f_1^s b_{11}^{ss}(y_1^{ss}+y_1^{sr})$ is emissions created in region *s*' 1st sector in its final goods production for both the 1st sector's domestic sales and outflow. The second element, $f_1^s b_{12}^{ss}(y_2^{ss}+y_2^{sr})$, is region *s*' emissions from the production of gross output of the 1st sector in region *s* used as intermediate input to produce its 2nd sector’s final goods for both the 2st sector's domestic sales and outflow. The third and fourth elements, $f_1^s b_{11}^{sr}(y_1^{rs}+y_1^{rr})$ and $f_1^s b_{12}^{sr}(y_2^{rs}+y_2^{rr})$, are region *s*' emissions from the production of gross output of the 1st sector used as intermediate input to produce region *r*’s final goods in its 1st and 2nd sectors respectively. Other elements have similar economic interpretations

Therefore, summing up the first row of the matrix, we have region *s*' total emissions produced by its 1st sector. Adding up all elements in the first column equals the global emissions to produce region *s* 1st sector’s final goods.

In summary, the sum of the $\hat{F}B\hat{Y}$ matrix across columns along a row accounts for how each region's emissions produced in a particular sector is distributed by the consumption of the sector itself and all its downstream regions/sectors. It traces forward industrial linkages across all downstream regions/industries from an emissions producer’s perspective because not all the emissions produced by the producer is for his own consumption. The sum of the $\hat{F}B\hat{Y}$ matrix across the rows along a column accounts for all upstream regions/sectors’ emissions to the production of a specific region/sector’s final goods; it traces backward industrial linkages across upstream regions/industries (as different stage of production) from a domestic supply chain’s perspective.

Therefore, the producer’s perspective (summing across columns along a row) decomposes each region's total emissions by industry according to where the consumption is made, while the supply chain perspective (summing across rows along a column) decomposes the total global emissions from the production of a region/sector's final goods and services according to where each of the needed intermediate inputs is produced (into different region/sector sources).

These two different ways to decompose global total emissions each has its own interpretations and thus different roles in environment policy analysis. The decomposition of emissions by producing industry can address questions such as "who generates the emissions for whose consumption?" thus providing a starting point for the discussion of shared responsibility between producer and consumer at industry level; while the decomposition of total emissions generated by a final product is able to answer questions such as "what are the country emissions level and its (region/energy type) source structure and attribute the total emissions of a final product to each stage of production in the domestic supply chain, thus providing facts that help better understanding of the common but differentiated responsibilities among different production stages along each domestic supply chain.

With a clear understanding of how total regional emissions by industry and total country emissions by final goods production at the region-sector level can be correctly estimated and decomposed by the standard Leontief method (equation (3) or the $\hat{F} B\hat{Y}$ matrix), we formally specify the decomposition methods used in this paper and their relation to other IRIO model based methods proposed in the literature.

2.2 Decompose an industry's total emissions based on forward industrial linkage

Extending equation (2) to a G region country, the gross output production and use balance, or the row balance condition of an IRIO table becomes:

$$X^{s} = (I - A^{ss})^{-1}Y^{ss} + (I - A^{ss})^{-1}E^{s*} \qquad (4)$$

Where $E^{s*} = \sum_{s \neq r}^{G} E^{sr}$ is total gross outflow of region *s*.

It can be show that

$$(I - A^{ss})^{-1} E^{s*} = (I - A^{ss})^{-1} (\sum_{r \neq s}^{G} Y^{sr} + \sum_{r \neq s}^{G} A^{sr} X^{r}) = \sum_{r \neq s}^{G} B^{ss} Y^{sr} + \sum_{r \neq s}^{G} B^{sr} Y^{rr} + \sum_{r \neq s}^{G} \sum_{t \neq s,r}^{G} B^{st} Y^{tr}$$
$$+ \sum_{r \neq s}^{G} B^{sr} Y^{rs} + \sum_{t}^{G} B^{sr} A^{rs} (I - A^{ss})^{-1} Y^{ss} \qquad (5)$$

Insert (5) into (4), pre-multiply direct emissions intensity diagonal matrix $\hat{F}$, we obtain the equation that decomposes total emissions by industry into different components as follows:

$$P^{s} = \hat{F}^{s} X^{s} = \hat{F}^{s} L^{ss} Y^{ss} + \hat{F}^{s} L^{ss} \sum_{r \neq s}^{G} A^{sr} \sum_{t}^{G} B^{rt} Y^{ts} + \hat{F}^{s} \sum_{r \neq s}^{G} B^{ss} Y^{sr} + \hat{F}^{s} \sum_{r \neq s}^{G} B^{sr} Y^{rr} + \hat{F}^{s} \sum_{r \neq s}^{G} \sum_{t \neq s,r}^{G} B^{st} Y^{tr} \qquad (6)$$

where, $L^{ss} = (I - A^{ss})^{-1}$ is the local Leontief inverse.

There are total five terms in equation (6), each of them represents emissions generated by the industry in its production of final goods and services to satisfy different segments of the country's market. The first term is emissions generated by the production of the source region produced final goods and services that sale at the source region's market; the second term is emissions generated by the production of intermediate goods outflow which used by other regions to produce goods and service delivered back to the source region either as final goods inflows or as intermediate goods inflows (which in turn used in the production of the source region's goods consumed in the local market). The third term is emissions generated by the production of region *s*' final goods outflow to each of its trading regions. The fourth term is emissions generated by the production of region *s*' intermediate goods outflow used by each of its trading partner regions to produce their locally consumed goods and services. The last term is emissions generated by the production of region *s*' intermediate goods outflow to the third region producing their outflow to each of its trading partner regions. Note the summation in the last three terms indicates these emissions generated by outflow production can be further split into each trading partner's market. The disaggregated accounting for total emissions by industry based on forward industrial linkage made by equation (6) is also diagrammed in figure 1. The number in the lowest level box corresponding the terms in equation (6).

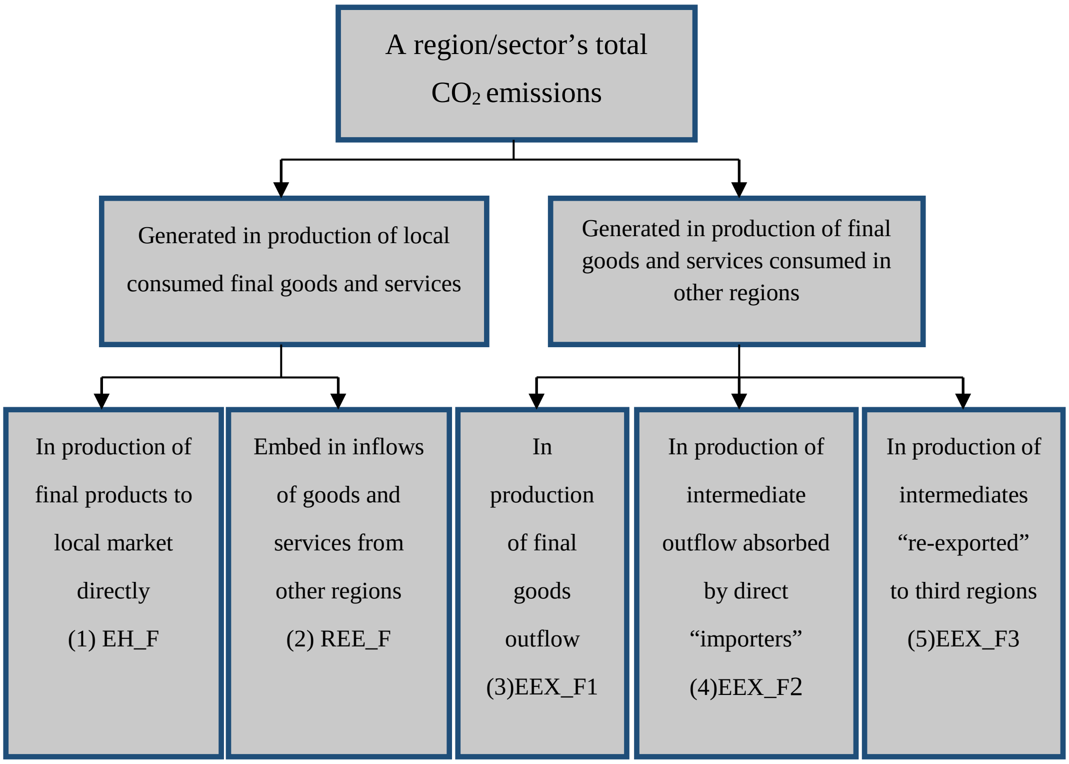


Figure 2 CO_2 emissions production by sources of final demand-Forward industrial linkage based decomposition

2.3 Decompose total emission generated from a final goods based on backward industrial linkage

We will estimate the total emissions generated by a final product along domestic supply chain that identified by the last stage of production: a particular industry *i* located in a specific region *s*, denoted as y_i^s to be consistent in notation with previous section. To produce y_i^s, activities x_j^s in industry j = 1,…, N in each of the region s = 1,…,G are needed (production stages in the domestic supply chain are identified by each of x_j^s, the maximum production stage of a specific supply chain in this accounting framework is GN, assuming industries with the same classification but locate in different regions produce differentiate products so is located in different production stage of the domestic supply chain). We first need to know the levels of all gross output x_j^s associated with the production of y_i^s. This can be estimated by standard Leontief methods specified in equations (2) and (3) we discussed in details earlier. To be more specific to our current analysis, let to us extend equation (2) and (3) to cover any number of regions(G) and sectors (N), then we obtain following equations:

$$\begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^G \end{bmatrix} = \begin{bmatrix} B^{11} & B^{12} & \cdots & B^{1G} \\ B^{21} & B^{22} & \cdots & B^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ B^{G1} & B^{G2} & \cdots & B^{GG} \end{bmatrix} \begin{bmatrix} Y^1 \\ Y^2 \\ \vdots \\ Y^G \end{bmatrix} \tag{7}$$

$$\begin{aligned} \hat{F} B\hat{Y} &= \begin{bmatrix} \hat{F}^1 & 0 & \cdots & 0 \\ 0 & \hat{F}^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \hat{F}^G \end{bmatrix} \begin{bmatrix} B^{11} & B^{12} & \cdots & B^{1G} \\ B^{21} & B^{22} & \cdots & B^{2G} \\ \vdots & \vdots & \ddots & \vdots \\ B^{G1} & B^{G2} & \cdots & B^{GG} \end{bmatrix} \begin{bmatrix} \hat{Y}^1 & 0 & \cdots & 0 \\ 0 & \hat{Y}^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \hat{Y}^G \end{bmatrix} \\ &= \begin{bmatrix} \hat{F}^1 B^{11} \hat{Y}^1 & \hat{F}^1 B^{12} \hat{Y}^2 & \cdots & \hat{F}^1 B^{1G} \hat{Y}^G \\ \hat{F}^2 B^{21} \hat{Y}^1 & \hat{F}^2 B^{22} \hat{Y}^2 & \cdots & \hat{F}^2 B^{2G} \hat{Y}^G \\ \vdots & \vdots & \ddots & \vdots \\ \hat{F}^G B^{G1} \hat{Y}^1 & \hat{F}^G B^{G2} \hat{Y}^2 & \cdots & \hat{F}^G B^{GG} \hat{Y}^G \end{bmatrix} \end{aligned} \tag{8}$$

With G regions and N sectors, A, B, $\hat{F}$ and $\hat{Y}$ are all GN×GN matrices. B^{sr} denotes the N×N block Leontief inverse matrix, which is the total requirement matrix that describes the amount of gross output in producing region *s* required for a one-unit increase in the final demand in destination region *r*. F^s is a 1 by N vector of direct emissions intensity in region *s*, placed in the diagonal of the GN by GN matrix of $\hat{F}$. $X^s = \sum_r^G X^{sr}$ is an N×1 vector that gives region *s*' total gross output; $Y^s = \sum_r^G Y^{sr}$ is also an N×1 vector that gives the country use of region *s*' final goods. Each column of the $B\hat{Y}$ matrix of Equation (8) is a GN by 1 vector, the number of non-zero elements in such a column vector represent the number of production stages in our accounting framework for the domestic supply chain of a particular final good and services y_j^s.

Based on equation (8), we can decompose the total emissions of a final goods and services by production stages in domestic supply chain based on backward industrial linkage as follows:

$$P_c(Y^s) = \hat{F}_c^s B^{ss} Y^s + \sum_{r \neq s}^{G} \hat{F}_c^r B^{rs} Y^s \qquad (9)$$

The first term in equation (9) is diagonal elements in the last matrix of equation (8), representing emissions generated in local production process; while the second term in equation (9) are the sum of off-diagonal elements across the row and along the column in the last matrix of equation (8), measuring emissions generated in other regions' production process. The summation in the second term indicates these emissions generated from other regions' production can be further split into each of the source regions. The decomposition of total emissions by the production of a final goods and services in a domestic supply chain based on backward industrial linkage made by equations (9) is also diagrammed in figure 2.

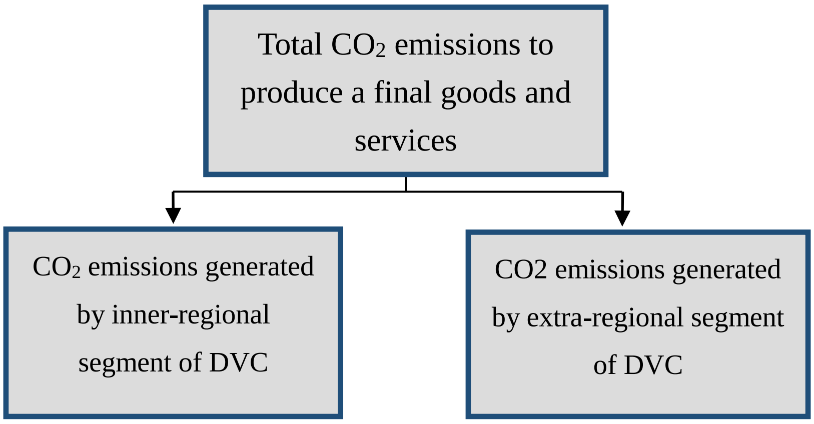


Figure 3 CO_2 emissions in domestic value chains-backward industrial linkage based decomposition

2.4 CO_2 emissions in the production of gross exports-backward industrial linkage based decomposition

Following the innovative decomposition method proposed by Wang *et al.* (2013), we define our measures based on backward industrial linkage as follows:

$$\begin{aligned} EEX^{sr} &= (F^s B^{ss})^T \# Y^{sr} + (F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rr}) \\ &+ (F^s L^{ss})^T \# \left\{ (A^{sr} B^{rr} \sum_{t \neq s,r}^{G} Y^{rt}) + (A^{sr} \sum_{t \neq s,r}^{G} B^{rt} Y^{tt}) + (A^{sr} \sum_{t \neq s,r}^{G} \sum_{u \neq s,t}^{G} B^{rt} Y^{tu}) \right\} \end{aligned} \tag{10}$$

where, "#" represents an element-wise matrix multiplication operation[23]. To facilitate the understanding of the three terms in the emissions inter-regional trade measure defined in equation (10), we provide the following intuitive interpretations:

The first term, $(F^s B^{ss})^T \# Y^{sr}$, is domestic emissions generated by production of region *s* final exports to region *r* The second term, $(F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rr})$, is domestic

---

[23] For example, when a matrix is multiplied by $n \times 1$ column vector, each row of the matrix is multiplied by the corresponding row element of the vector.

emissions generated by the production of region *s*’ intermediate outflow used by direct “importer” (region *r*) to produce final goods and consumed in region *r*. The third term, $(F^{s}L^{ss})^{T}\#\{\ldots\}$ is domestic emissions generated by the production of region *s’* intermediate outflow used by the direct importer (region *r*) to produce intermediate or final goods and services “re-exports” to third region *t*. The three elements in the parenthesis, $A^{sr}B^{rr}\sum_{t\neq s,r}^{G}Y^{rt}$, $A^{sr}\sum_{t\neq s,r}^{G}B^{rt}Y^{tt}$, and $A^{sr}\sum_{t\neq s,r}^{G}\sum_{u\neq s,t}^{G}B^{rt}Y^{tu}$ are how the “re-exports” are produced in region *r* by using region *s*’ intermediate outflow as inputs. They are used to produce final goods “re-exports”, intermediate goods “re-exports” for third countries’ domestically consumed final goods, and intermediate goods “re-exports” for third countries’ final goods outflow, respectively.

Define returned domestic emissions based on backward industrial linkages from region *s* to region *r* that is first exported but ultimately returned and absorbed at home as:

$$
\begin{aligned}
REE\_B^{sr} &= (F^{s}L^{ss})^{T}\#A^{sr}\sum_{t}^{G}B^{rt}Y^{ts} \\
&= (F^{s}L^{ss})^{T}\#(A^{sr}B^{rr}Y^{rs}) + (F^{s}L^{ss})^{T}\#(A^{sr}\sum_{t\neq s,r}^{G}B^{rt}Y^{ts}) + (F^{s}L^{ss})^{T}\#(A^{sr}B^{rs}Y^{ss})
\end{aligned}
\tag{11}
$$

To completely measure total emissions from the production of a region’s gross exports, emissions generated in other regions that provide intermediate inputs for the “exporting” region also have to be account for. The emissions produced from other region embodied in a region’s gross exports (FEE) can be defined as

$$
\begin{aligned}
FEE^{sr} &= (F^{r}B^{rs})^{T}\#Y^{sr} + (F^{r}B^{rs})^{T}\#(A^{sr}L^{rr}Y^{rr}) \\
&+ (\sum_{t\neq s,r}^{G}F^{t}B^{ts})^{T}\#Y^{sr} + (\sum_{t\neq s,r}^{G}F^{t}B^{ts})^{T}\#(A^{sr}L^{rr}Y^{rr})
\end{aligned}
\tag{12}
$$

Each term in equation (12) has an intuitive interpretation. The first term,

$(F^r B^{rs})^T \# Y^{sr}$, is emissions of “importer” (region *r*) emissions embodied in region *s*’ final outflow to region *r*. The second term, $(F^r B^{rs})^T \# (A^{sr} L^{rr} Y^{rr})$, is emissions of “importer” (region *r*) embodied in region *s*’ intermediate outflow to region *r*, these intermediate inputs are then used by region *r* to produce its domestic final goods. The third term, $(\sum_{t \neq s,r}^{G} F^t B^{ts})^T \# Y^{sr}$, is emissions from the third region *t* embodied in region *s*’ final outflow to region *r*.. The last term, $(\sum_{t \neq s,r}^{G} F^t B^{ts})^T \# (A^{sr} L^{rr} Y^{rr})$, is emissions from the third region *t* embodied in region *s*’ intermediate outflow to region *r*., these intermediate goods are then used by region *r* as inputs to produce its domestic final goods.

Combine equations (10), (11) and (12), we decompose the total emissions generated from the production of a region’s gross exports to its trading partner regions as follows:

$$
\begin{aligned}
& P(E^{sr}) = (F^s B^{ss})^T \# Y^{sr} + (F^s L^{ss})^T \# (A^{sr} B^{rr} Y^{rr}) \\
& + (F^s L^{ss})^T \# \left\{ (A^{sr} B^{rr} \sum_{t \neq s,r}^{G} Y^{rt}) + (A^{sr} \sum_{t \neq s,r}^{G} B^{rt} Y^{tt}) + (A^{sr} \sum_{t \neq s,r}^{G} \sum_{u \neq s,t}^{G} B^{rt} Y^{tu}) \right\} + (F^s L^{ss})^T \# A^{sr} \sum_{t}^{G} B^{rt} Y^{ts} \quad (13) \\
& (F^r B^{rs})^T \# Y^{sr} + (F^r B^{rs})^T \# (A^{sr} L^{rr} Y^{rr}) + (\sum_{t \neq s,r}^{G} F^t B^{ts})^T \# Y^{sr} + (\sum_{t \neq s,r}^{G} F^t B^{ts})^T \# (A^{sr} L^{rr} Y^{rr})
\end{aligned}
$$

The first four terms of equation (13) produce emissions within the “exporting” region, which is a by-product in generating the “exporting” region’s GDP; the last four terms in equation (13) produce emissions within the other regions, but also create GDP for these regions who provide intermediate inputs for the “exporting” region. The decomposition made in equation (13) is also diagrammed in figure 3.The number in the lowest level box corresponding the terms in equation (13).

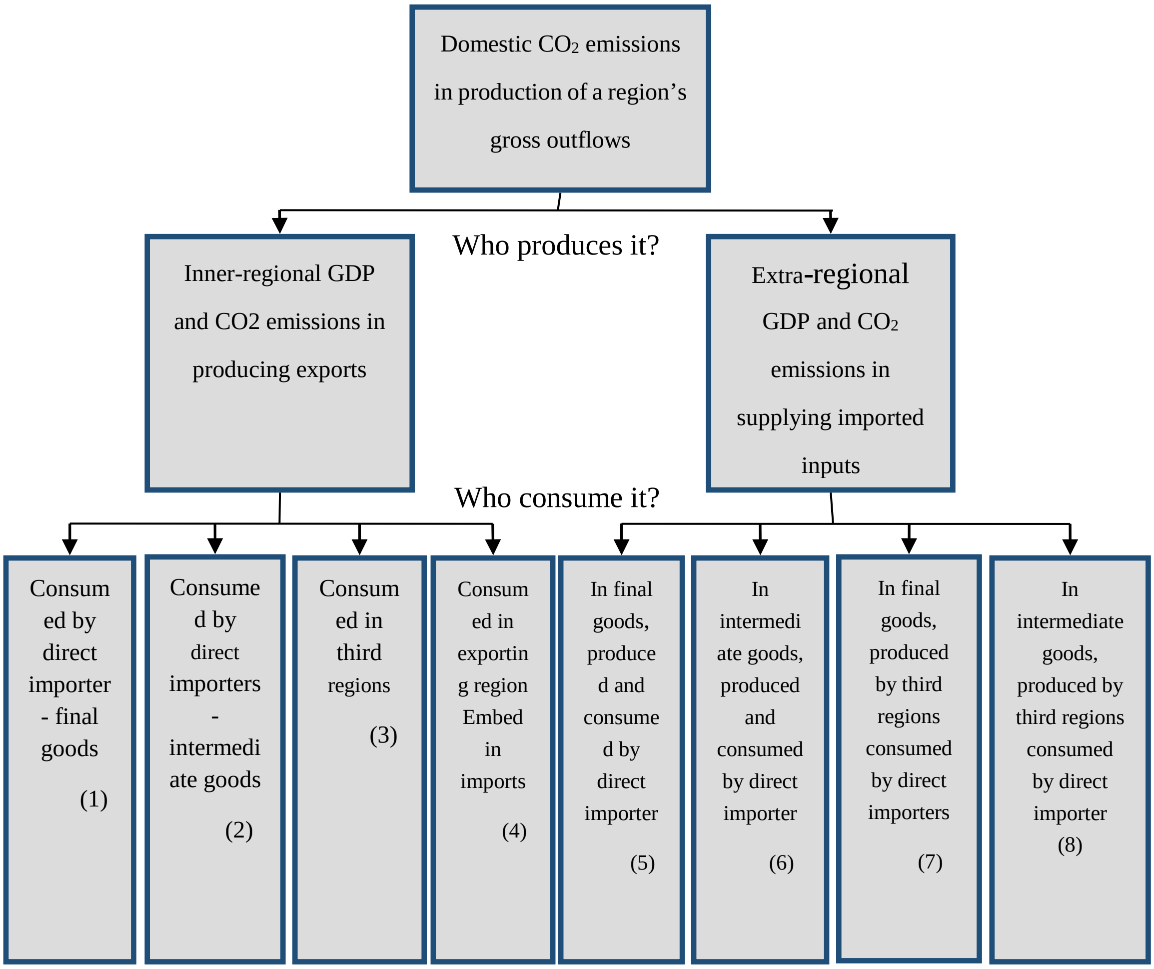


Figure 4 CO_2 emissions in the production of gross exports-backward industrial linkage based decomposition

3. Empirical Results

3.1 Who produces CO_2 emissions for whom in domestic value chains

3.1.1 Regional CO_2 emissions for different final demand

In this section we use the MRIO model to demonstrate how the first accounting framework proposed above can help to gain a better understanding of the relationship between DVCs and CO_2 emissions base on the forward linkage decomposition.

Table 1 CO$_2$ emission production by sources of final demand-Forward industrial linkage based decomposition

	2007							2010						
CO2 Emissions (10KT)	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	EF_F	Sum	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	EF_F	Sum
North East	30,398	474	9,512	13,775	3,244	13,464	70,867	42,129	823	7,619	15,000	3,028	17,381	85,980
North Municipaliti	6,014	183	4,311	4,079	766	5,560	20,913	8,285	297	3,328	4,463	745	5,850	22,968
North Coast	44,201	2,746	7,607	21,955	4,632	40,246	121,387	53,807	3,386	8,750	33,591	6,183	42,281	147,998
East Coast	47,373	828	5,548	7,877	1,991	38,423	102,040	51,130	945	6,821	11,306	2,559	41,115	113,876
South Coast	26,351	434	5,970	7,970	1,450	15,663	57,838	28,538	462	5,749	11,066	2,041	21,047	68,903
Central	59,241	3,757	7,432	26,195	3,650	50,431	150,706	88,540	5,746	11,910	41,038	5,876	36,342	189,452
North West	22,785	768	13,315	19,368	3,742	17,667	77,645	39,696	1,505	15,134	26,038	4,321	23,461	110,155
South West	35,241	784	9,596	9,750	2,005	17,950	75,326	51,330	1,035	15,333	14,447	2,740	14,130	99,015
National Total	271,604	9,974	63,291	110,969	21,480	199,404	676,722	363,455	14,199	74,644	156,949	27,493	201,605	838,345
Share (%)	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	EF_F	Sum	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	EF_F	Sum
North East	42.9%	0.7%	13.4%	19.4%	4.6%	19.0%	100.0%	49.0%	1.0%	8.9%	17.4%	3.5%	20.2%	100.0%
North Municipaliti	28.8%	0.9%	20.6%	19.5%	3.7%	26.6%	100.0%	36.1%	1.3%	14.5%	19.4%	3.2%	25.5%	100.0%
North Coast	36.4%	2.3%	6.3%	18.1%	3.8%	33.2%	100.0%	36.4%	2.3%	5.9%	22.7%	4.2%	28.6%	100.0%
East Coast	46.4%	0.8%	5.4%	7.7%	2.0%	37.7%	100.0%	44.9%	0.8%	6.0%	9.9%	2.2%	36.1%	100.0%
South Coast	45.6%	0.8%	10.3%	13.8%	2.5%	27.1%	100.0%	41.4%	0.7%	8.3%	16.1%	3.0%	30.5%	100.0%
Central	39.3%	2.5%	4.9%	17.4%	2.4%	33.5%	100.0%	46.7%	3.0%	6.3%	21.7%	3.1%	19.2%	100.0%
North West	29.3%	1.0%	17.1%	24.9%	4.8%	22.8%	100.0%	36.0%	1.4%	13.7%	23.6%	3.9%	21.3%	100.0%
South West	46.8%	1.0%	12.7%	12.9%	2.7%	23.8%	100.0%	51.8%	1.0%	15.5%	14.6%	2.8%	14.3%	100.0%
National Total	40.1%	1.5%	9.4%	16.4%	3.2%	29.5%	100.0%	43.4%	1.7%	8.9%	18.7%	3.3%	24.0%	100.0%
Change rate between 2007 and 2010	Change rate of CO2 emisions between 2007 and 2010							Change rate of shares between 2007 and 2010						
	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	EF_F	Sum	EH_F	REE_F	EEX_F1	EEX_F2	EEX_F3	EF_F	Sum
North East	39%	74%	-20%	9%	-7%	29%	21%	14%	43%	-34%	-10%	-23%	6%	
North Municipaliti	38%	62%	-23%	9%	-3%	5%	10%	25%	48%	-30%	0%	-11%	-4%	
North Coast	22%	23%	15%	53%	33%	5%	22%	0%	1%	-6%	25%	9%	-14%	
East Coast	8%	14%	23%	44%	29%	7%	12%	-3%	2%	10%	29%	15%	-4%	
South Coast	8%	6%	-4%	39%	41%	34%	19%	-9%	-11%	-19%	17%	18%	13%	
Central	49%	53%	60%	57%	61%	-28%	26%	19%	22%	27%	25%	28%	-43%	
North West	74%	96%	14%	34%	15%	33%	42%	23%	38%	-20%	-5%	-19%	-6%	
South West	46%	32%	60%	48%	37%	-21%	31%	11%	0%	22%	13%	4%	-40%	
National Total	34%	42%	18%	41%	28%	1%	24%	8%	15%	-5%	14%	3%	-18%	

Table 1 shows how much the CO_2 emissions are induced by different sources of final demand through in the eight regions for both 2007 and 2010. Total production based CO2 emissions can by decomposed into 5 parts (referring to Figure 2) according to sources of final demand it satisfies. The structure and changing pattern among these five final demand sources between 2007 and 2010 are shown in the middle and bottom parts of Table 1. In order to see the structure changes easier, we draw two figures to show both the structures and the changes in emissions by regions.

From Figure 1, it is easy to see that the Central region produce the most CO_2 emissions in China followed by the North Coast region, while the North Municipalities account for the smallest part of total CO_2 emissions in both 2007 and 2010. **(1)** Obviously, for all regions and for both years, the CO_2 emission generated by the production of local produced goods and services that sale directly at local market (EH_F) account for the majority of the total emissions, especially for South West region (51.8%), North East region (49.0%) and Central region (46.7%) account for nearly 50% of the total emissions in 2010. There is no surprising because most regions' production is mainly for fulfilling its local use. **(2)** The share of CO_2 emissions generated by the production of intermediate outflow absorbed by the direct "import" region (EEX_F2) contribute the largest share of CO_2 emissions generated by the products consumed in other regions comparing to CO_2 emissions production induced by the other two sources of external final demands (EEX_F1 and EEX_F2). North West region (23.6%), North Coast region (22.7%) and Central region (21.7%) have a large portion of emissions production for satisfying intermediate products demand of their "import" regions. It implies that the participation of all the regions (except South West region) in DVCs is mainly through providing intermediate outflow, namely more CO_2 emissions is generated by this route. **(3)** In contrast, South West region's CO_2 emissions for "export" are mainly generated by the final demand of the direct "importer" (15.5%). Apparently, CO_2 emissions in production for final goods outflow (EEX_F1) are the second largest contributor in all regions. CO_2 emissions in the North Municipalities (14.5%) and North West region (13.7%) are generated by the production of outflow to meet final demand of their direct "importer" as South West region does, but with a much higher portion of such emission generated by the production of intermediate outflow. **(4)** The share for EEX_F3 (emissions generated by the production of intermediates that "re-exported" to third regions) is lower than EEX_F1 and EEX_F2, and the share for REE_F (emission generated by the production of intermediate goods outflow which used by other regions to produce goods and service shipped back to the source region either as final goods imports or as intermediate goods imports is the smallest. It implies that the China's domestic value chain is not such complicated. In summary, it illustrates that a region's production based CO_2 emissions depends not only on the energy efficiency of its production technology, but also on its position and participation in DVCs.

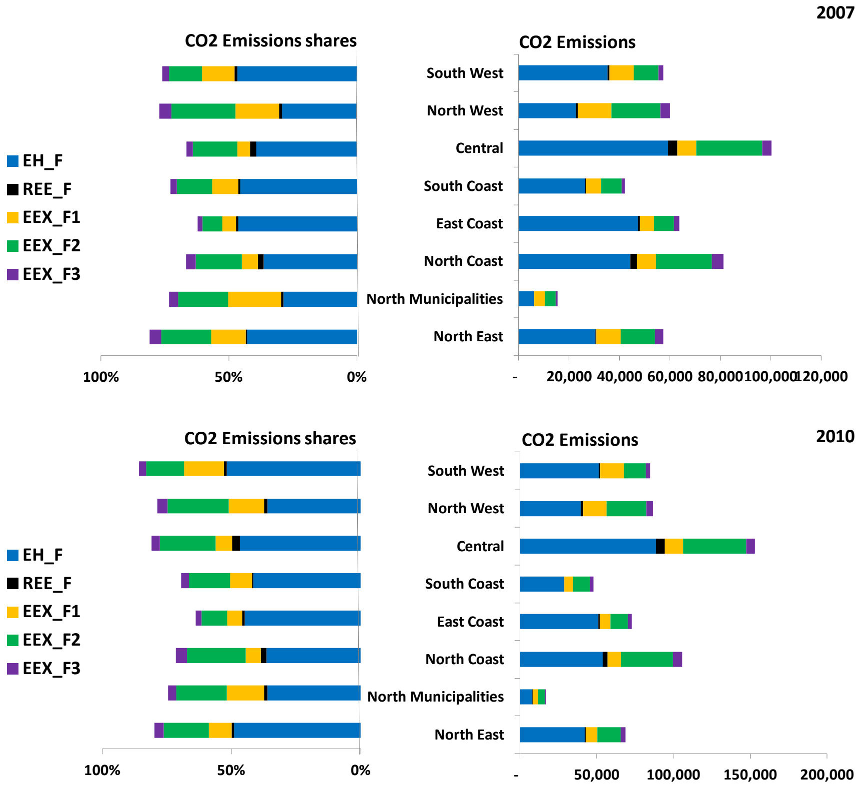


Figure 5 CO_2 emissions induced by different final demand in 2010

When looking at the changing pattern of the CO_2 emissions between 2007 and 2010, Figure 6 provides a clear view of the changes by different final demand for each region. **(1)** CO_2 emissions embodied in production for all sources of final demands experience an increase except emissions for satisfying final goods and services of the direct "importers" (EEX_F1). EEX_F1 decrease a lot in both the North Municipalities and North East region with 30% and 34% loss respectively. Similarly, EEX_F1 in South Coast region also faces a large decline by 19%. **(2)** It is interesting that the changes in shares of CO_2 emissions shows very different pattern across regions. Obviously, changes in shares of CO_2 emissions can be classified into three patterns: **1)** "increase in CO_2 emissions shares for local demand and decrease in CO_2 emissions shares for external demand", including the North Municipalities, North East region and North West region. The production of these regions turns to satisfy their local final demand more, which means the participation of these regions in DVCs declines in 2010. **2)** "Decrease in CO_2 emissions shares for local demand and increase in CO_2 emissions shares for external demand", see North Coast region, East Coast region and South Coast region. This change pattern reflects the fact that these coast regions have been involved in DVCs more deeply than before. Especially, the share of EEX_F2 increases more than the shares of EEX_F1 and EEX_F3, more of their emission production is for satisfying the demand of intermediate products from other regions. **3)** "Increase in emissions shares for both local and external demand", for instance, the shares of emissions of Central region and South West region face a great increase in nearly all source of final demand, especially for Central region' emissions induced by external demand (EEX_F1, EEX_F2 and EEX_F3) and South West region' s emissions induced by the demand of final goods and service from other regions (EEX_F1). In summary, all the regions with the last two change patterns show positive and large change rates in shares of EEX_F2 and EEX_F3, which clearly reflects the increasing complexity in DVCs since more intermediate goods and services are cross regional border more than once and "re-exported" to third regions for further processing in the domestic production networks. **(3)** In addition, the share for REE_F also experiences great increase in most regions except South Coast region (-11%) and South West (0%), such as the North Municipalities (48%), North East region (43%), North West (38%) and Central region (22%), although the absolute level of this share is extremely low (see the yellow arrowed bars). This implies that the regional imported final goods tends embody more its own emissions generated by its intermediates goods outflow.

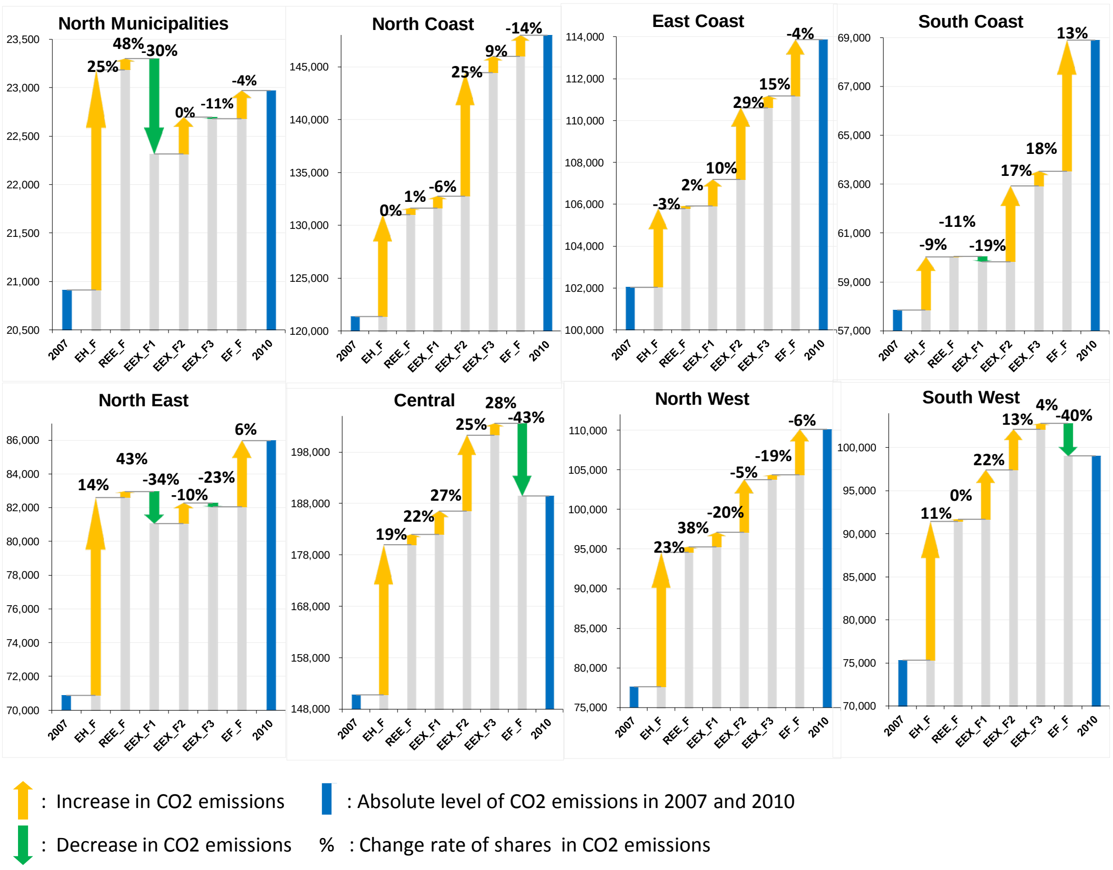


Figure 6 Changing patterns of CO_2 emissions induced by different final demand between 2007 and 2010

3.1.2 Inter-regional trade in CO_2 emissions based on forward industrial linkage

Base on the first framework in Figure 2 discussed in section 3, we can also get the deeper decomposition both at inter-regional and at industrial level. This section we mainly focus on the inter-regional level and leave the industrial level analysis in the next section. After a brief overview of the CO_2 emissions generated in production for five different final demands in each region both locally and externally, one may be wondering about inter-regional bilateral trade in CO_2 emissions in detail. Figure 7 illustrates the inter-regional trade in CO_2 emissions between regions for 2002 and 2007, with the bubble size representing the absolute inter-regional bilateral flow of CO_2 emissions. The darker the bubble is, the higher the carbon intensity the region has. In addition, the donut chart inside each bubble shows the structures of emissions by three external final demands. Here we only provide the donut charts for some top larger bubbles.

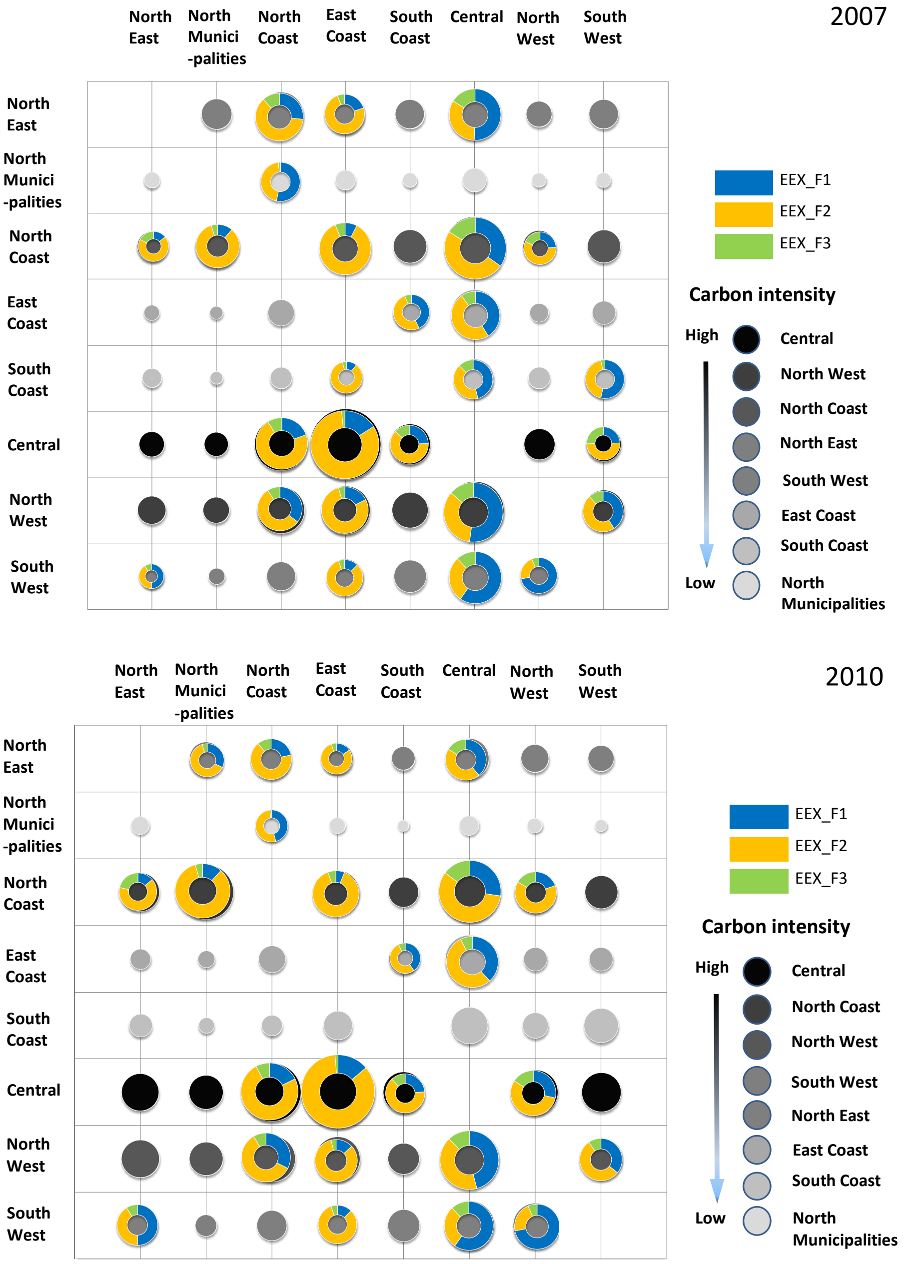


Figure 7 Inter-regional bilateral trade in CO_2 emissions based on forward industrial

linkage

(1) Obviously, as for carbon intensity, Central region and North West region have higher carbon intensity with deep dark bubbles in 2007, while the carbon intensities of both the North Municipalities and South Coast region are the lowest among all regions. However, in 2010, North Coast region has replaced North West region as the region with the second highest carbon intensity. Similarly, South West region replaced North East region becoming the region with the fourth highest carbon intensity.

(2) When looking at the CO_2 emissions from the outflow side, we will find that Central region, North West region and North Coast region are the main inter-regional “exporters” in both two years with an increasing trend. There are no significant structure changes in the CO_2 emissions induced by external final demands in these three regions. The CO_2 emissions generated by the production of intermediate outflow absorbed by the direct “import” region (EEX_F2) plays a dominant role in embodied CO_2 emissions. This result is consistent with the fact that many inland regions have been deeply involved in domestic supply chains by providing more intermediate products to other regions. To be more specificly, North West region, the largest energy-base region, Central region and North Coast region are likely to be located at the upstream of China’s domestic supply chains by providing a large proportion of intermediate products to other regions. The CO_2 emissions outflow from coastal regions (East Coast and South Coast) and the North Municipalities are relatively small, since the coastal regions are international export-oriented economies with a large share of manufacturing for international (not inter-regional) exports in their total products. It comes as no surprise that the North Municipalities, one of the quickly expanding urban agglomeration areas have a low inter-regional trade in CO_2 emissions, given the region’s services-oriented economy.

(3) When talking about the bilateral trade in CO_2 emissions in terms of inter-regional import, Central region tends to import more CO2 emissions from North Coast region, North West region and South West region, and the emissions embodied in products “imported” from North West region and South West region are mainly induced for satisfying the demand of final goods and service rather than intermediate products, while the CO_2 emissions inflow from North Coast region is generated in the intermediate products for further production in Central region. Besides Central region, the three developed coastal regions (East Coast, South Coast, and North Coast) have higher embodied CO_2 emissions in inter-regional import than the inland regions and the North Municipalities. The most CO_2 emissions inflow is embodied in intermediate products in these coastal regions, and Central region and North West region are their major inter-regional import partners.

Table 2 Inter-regional bilateral trade in CO₂ emissions

2010	EEX_F							
	North East	North Municipalit	North Coast	East Coast	South Coast	Central	North West	South West
North East	0	3907.5304	5299.075	3429.39	1975.4051	5804.198	2792.2804	2439.5641
North Municipalit	1163.141	0	3363.833	909.92	453.8837	1373.231	765.6742	507.0257
North Coast	5342.404	10665.2591	0	6632.389	3243.2963	12708.821	6025.9775	3905.612
East Coast	1509.442	1034.7824	2621.031	0	3157.1768	8338.06	1999.9854	2025.4777
South Coast	1905.771	875.3433	1545.498	3012.279	0	4858.268	2372.9906	4286.6183
Central	5058.526	4198.5354	12291.009	18441.295	6029.0186	0	7205.3478	5599.8007
North West	5239.873	4118.2387	7761.295	7187.28	3567.2235	11694.75	0	5923.5476
South West	4212.836	1653.5422	3254.525	3958.508	3670.9597	8656.506	7113.1258	0
>	EEX_F2							
	North East	North Municipalit	North Coast	East Coast	South Coast	Central	North West	South West
North East	0	1250.3376	1152.9701	542.2562	572.0048	2256.686	1163.7155	681.3656
North Municipalit	425.0856	0	1542.2967	156.0372	174.0304	502.9522	332.5996	195.3619
North Coast	739.7299	1247.6371	0	404.9207	737.9425	3481.5856	1180.8993	957.5263
East Coast	440.6713	187.1321	475.3664	0	1272.6225	3188.0975	698.9703	558.2908
South Coast	771.3669	148.1575	209.0581	230.1107	0	1634.6149	968.7252	1787.4327
Central	1353.8342	885.6711	2182.1991	2544.4359	1435.0418	0	2055.4397	1453.4751
North West	1790.0724	1418.7772	2514.8944	943.7382	987.7576	5365.3561	0	2113.2496
South West	2448.4496	724.1693	809.8087	422.5126	1111.3281	4673.4846	5142.7694	0
>	EEX_F2							
	North East	North Municipalit	North Coast	East Coast	South Coast	Central	North West	South West
North East	0	2462.1803	3559.485	2702.5641	1111.0212	2595.8403	1172.3591	1396.6042
North Municipalit	657.5467	0	1761.287	709.0302	203.1036	598.9452	321.5377	211.5364
North Coast	3458.2336	8957.0922	0	5855.6945	1953.3188	7355.2485	3847.2537	2163.9719
East Coast	732.2456	680.4325	1806.536	0	1655.022	4520.7712	897.3967	1013.5037
South Coast	847.7219	567.6147	1036.654	2671.0714	0	2593.1648	1020.0525	2329.7393
Central	2611.6543	2703.0139	9143.466	15656.6236	3869.7933	0	4005.8611	3047.1205
North West	2838.1535	2379.1214	4598.58	5965.7232	2102.6516	4918.7933	0	3234.7013
South West	1404.2136	723.0672	2042.938	3335.3462	2313.5076	3034.7258	1593.4985	0
>	EEX_F3							
	North East	North Municipalit	North Coast	East Coast	South Coast	Central	North West	South West
North East	0	195.0124	586.61948	184.56926	292.37921	951.6713	456.2059	361.5944
North Municipalit	80.50829	0	60.24897	44.85252	76.74973	271.3339	111.5369	100.1274
North Coast	1144.44053	460.5298	0	371.77356	552.03509	1871.9871	997.8245	784.1138
East Coast	336.52488	167.2177	339.12905	0	229.53223	629.1915	403.6184	453.6833
South Coast	286.68195	159.5711	299.78535	111.09715	0	630.4884	384.2129	169.4462
Central	1093.03743	609.8503	965.344	240.23519	724.18355	0	1144.047	1099.2051
North West	611.6468	320.3401	647.82082	277.81894	476.81427	1410.6006	0	575.5967
South West	360.17309	206.3057	401.77794	200.64924	246.12395	948.2961	376.8579	0
2010	EEX_F							
	North East	North Municipalit	North Coast	East Coast	South Coast	Central	North West	South West
North East	0	3907.5304	5299.075	3429.39	1975.4051	5804.198	2792.2804	2439.5641
North Municipalit	1163.141	0	3363.833	909.92	453.8837	1373.231	765.6742	507.0257
North Coast	5342.404	10665.2591	0	6632.389	3243.2963	12708.821	6025.9775	3905.612
East Coast	1509.442	1034.7824	2621.031	0	3157.1768	8338.06	1999.9854	2025.4777
South Coast	1905.771	875.3433	1545.498	3012.279	0	4858.268	2372.9906	4286.6183
Central	5058.526	4198.5354	12291.009	18441.295	6029.0186	0	7205.3478	5599.8007
North West	5239.873	4118.2387	7761.295	7187.28	3567.2235	11694.75	0	5923.5476
South West	4212.836	1653.5422	3254.525	3958.508	3670.9597	8656.506	7113.1258	0
>	EEX_F2							
	North East	North Municipalit	North Coast	East Coast	South Coast	Central	North West	South West
North East	0	1250.3376	1152.9701	542.2562	572.0048	2256.686	1163.7155	681.3656
North Municipalit	425.0856	0	1542.2967	156.0372	174.0304	502.9522	332.5996	195.3619
North Coast	739.7299	1247.6371	0	404.9207	737.9425	3481.5856	1180.8993	957.5263
East Coast	440.6713	187.1321	475.3664	0	1272.6225	3188.0975	698.9703	558.2908
South Coast	771.3669	148.1575	209.0581	230.1107	0	1634.6149	968.7252	1787.4327
Central	1353.8342	885.6711	2182.1991	2544.4359	1435.0418	0	2055.4397	1453.4751
North West	1790.0724	1418.7772	2514.8944	943.7382	987.7576	5365.3561	0	2113.2496
South West	2448.4496	724.1693	809.8087	422.5126	1111.3281	4673.4846	5142.7694	0
>	EEX_F2							
	North East	North Municipalit	North Coast	East Coast	South Coast	Central	North West	South West
North East	0	2462.1803	3559.485	2702.5641	1111.0212	2595.8403	1172.3591	1396.6042
North Municipalit	657.5467	0	1761.287	709.0302	203.1036	598.9452	321.5377	211.5364
North Coast	3458.2336	8957.0922	0	5855.6945	1953.3188	7355.2485	3847.2537	2163.9719
East Coast	732.2456	680.4325	1806.536	0	1655.022	4520.7712	897.3967	1013.5037
South Coast	847.7219	567.6147	1036.654	2671.0714	0	2593.1648	1020.0525	2329.7393
Central	2611.6543	2703.0139	9143.466	15656.6236	3869.7933	0	4005.8611	3047.1205
North West	2838.1535	2379.1214	4598.58	5965.7232	2102.6516	4918.7933	0	3234.7013
South West	1404.2136	723.0672	2042.938	3335.3462	2313.5076	3034.7258	1593.4985	0
>	EEX_F3							
	North East	North Municipalit	North Coast	East Coast	South Coast	Central	North West	South West
North East	0	195.0124	586.61948	184.56926	292.37921	951.6713	456.2059	361.5944
North Municipalit	80.50829	0	60.24897	44.85252	76.74973	271.3339	111.5369	100.1274
North Coast	1144.44053	460.5298	0	371.77356	552.03509	1871.9871	997.8245	784.1138
East Coast	336.52488	167.2177	339.12905	0	229.53223	629.1915	403.6184	453.6833
South Coast	286.68195	159.5711	299.78535	111.09715	0	630.4884	384.2129	169.4462
Central	1093.03743	609.8503	965.344	240.23519	724.18355	0	1144.047	1099.2051
North West	611.6468	320.3401	647.82082	277.81894	476.81427	1410.6006	0	575.5967
South West	360.17309	206.3057	401.77794	200.64924	246.12395	948.2961	376.8579	0

3.1.3 Regional CO_2 emission outflow and inflow by different GVC downstream routes (forward industrial linkage based decomposition)

Sectoral decomposition of regional CO_2 emissions outflow and inflow may help us to make a further study on the different patterns of CO_2 emissions generated by its production to satisfy different sources of final demand across sectors, and Figure 8 provides this information in depth by eight regions for year 2010. (1) For all regions, Sector 14 (Electricity, Gas and Water Supply) accounts for the majority of the regional production based CO_2 emissions both inflow and outflow. This is consistent with our intuition, since producing energy goods normally emits massive amount of CO_2. Meanwhile, the sources that generate CO_2 emissions from this sector is mainly from intermediate demand with relatively large contribution. The coastal regions (North Coast, East Coast and South Coast) and the North Municipalities are the leading regions in importing Sector 14's product (Electricity, Gas and Water Supply), on the contrary, the island regions (Central, North West and South West are the major "exporters" of Sector 14's product (Electricity, Gas and Water Supply). This phenomenon indicates that a region may not provide many energy goods to the domestic market directly, but its inter-regional exports of other goods may embody the emissions coming from its local production of energy when this region is deeply involved in DVCs. (2) When looking at the other sectors shown in the same figure, it's easy to find that Sector 9 (Metal products), Sector 8 (Non-metallic mineral products) and Sector 7 (Chemicals and Chemical Products) are the main emitter in inter-regional trade. This is not only because the emission intensity for these sectors is relatively high, but also their percentage as intermediate goods used in the domestic production network is also high. For example, the largest part of the emissions generated in Central region, North Coast region and North West region’s Sector 9, Sector 8 and Sector 7 are due to external intermediate goods demands. (3) In addition, Sector 2 (Mining and Quarrying) for Central and North West region, Sector 2 (Trade and Transport) for most regions also show relatively high CO2 emission with different patterns of the sources of final demand that driven the production. As shown in the above examples, the forward industrial linkage based decomposition can help us clearly understand who produces emissions for whom through what kind of routes in various global supply chains.

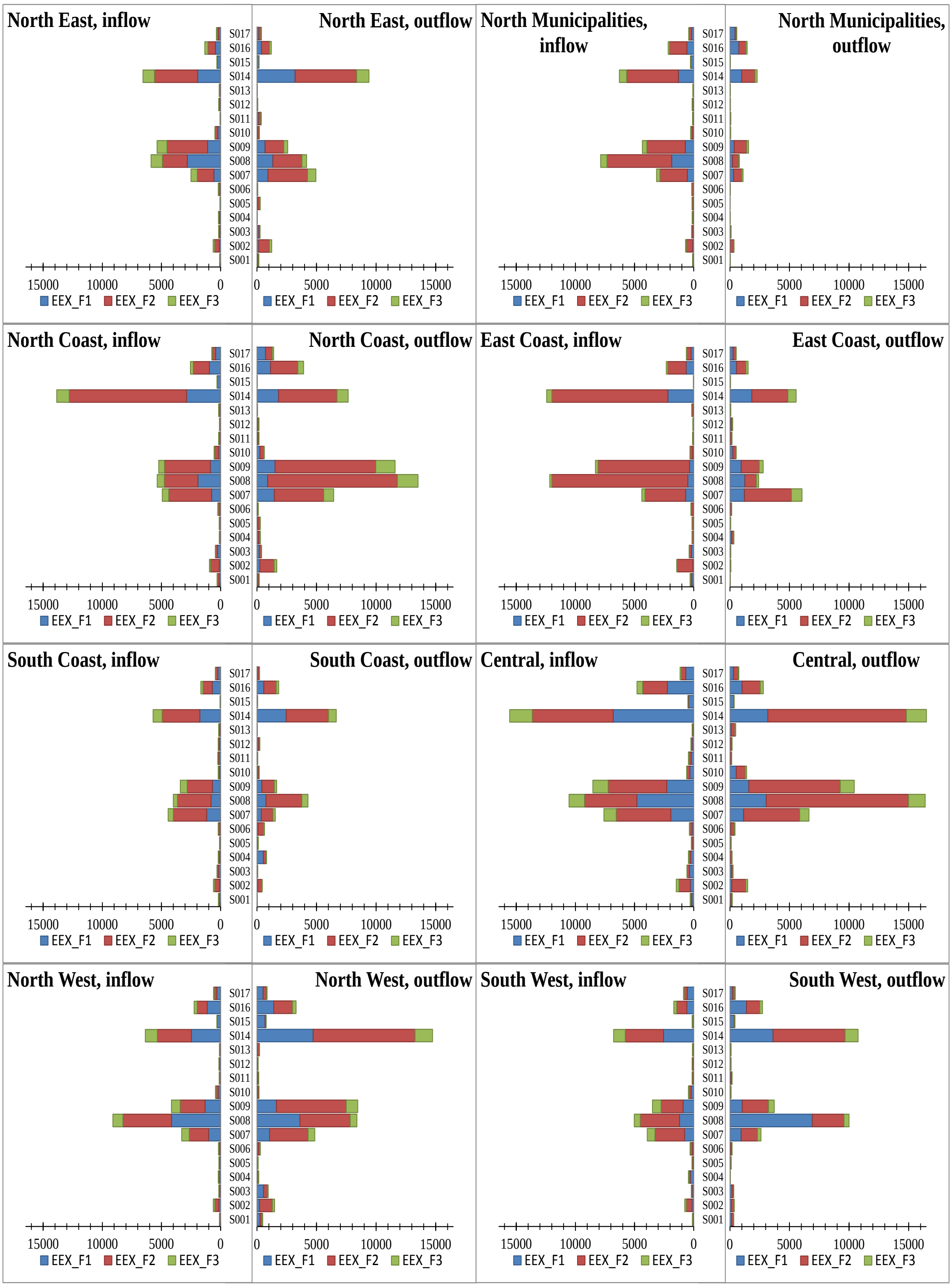


Figure 8 Regional CO_2 emission outflow and inflow by different GVC downstream routes (forward industrial linkage based decomposition, 2010, 10Kt)

3.2 CO_2 emissions in producing final goods and services in Domestic supply chains

3.2.1 CO_2 emissions generated in inner-regional and extra-regional segment of DVCs

Equation (9) as presented above, measures the total domestic emission for the production of final goods in region *s*. The decomposition results of total emission by the production of a final goods and services in a domestic supply chain based on backward industrial linkage made are shown in Table 3, also in Figure 9 more clearly.

Table 3 Inner and extra-regional CO_2 emissions to produce final goods and services-Backward industrial linkage based decomposition

	2007			2010			Change rate between 2007 and 2010 (%)		
CO2 emissions (10KT)	Inner-region	Extra-region	Total	Inner-region	Extra-region	Total	Inner-region	Extra-region	Total
North East	40158	7769	47927	50150	14314	64464	25%	84%	35%
North Municipaliti	10455	14119	24574	11826	24493	36319	13%	73%	48%
North Coast	53028	21204	74232	64258	27720	91978	21%	31%	24%
East Coast	53519	36026	89545	58671	41997	100668	10%	17%	12%
South Coast	32531	17080	49611	34525	18481	53006	6%	8%	7%
Central	68116	20411	88527	103020	29057	132077	51%	42%	49%
North West	36373	9525	45898	55415	18453	73868	52%	94%	61%
South West	45150	11855	57005	67153	17211	84364	49%	45%	48%
Share (%)	Inner-region	Extra-region	Total	Inner-region	Extra-region	Total	Inner-region	Extra-region	Total
North East	84%	16%	100%	78%	22%	100%	-7%	37%	
North Municipaliti	43%	57%	100%	33%	67%	100%	-23%	17%	
North Coast	71%	29%	100%	70%	30%	100%	-2%	6%	
East Coast	60%	40%	100%	58%	42%	100%	-2%	4%	
South Coast	66%	34%	100%	65%	35%	100%	-1%	1%	
Central	77%	23%	100%	78%	22%	100%	1%	-5%	
North West	79%	21%	100%	75%	25%	100%	-5%	20%	
South West	79%	21%	100%	80%	20%	100%	0%	-2%	

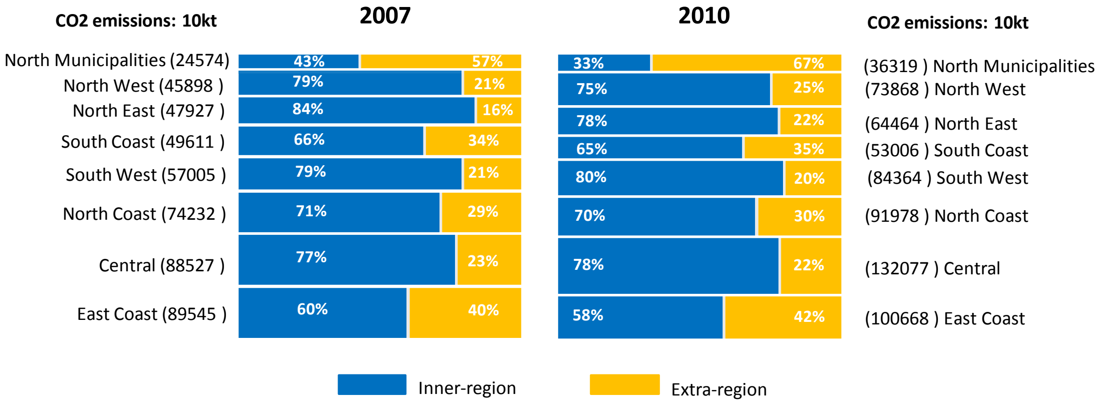


Figure 9 Inner and extra-regional CO_2 emissions to produce final goods and services-Backward industrial linkage based decomposition

(1) At the absolute level, East Coast region and Central region's production of final products no matter they are used locally or externally generates massive amount of total domestic CO_2 emissions followed by North Coast in both 2007 and 2010, which means these region's CO_2 for production of final goods cause more emissions compared with others. It depends on both a region's economic size and energy efficiency. In 2010, the situation changed, Central region exceeds East Coast region and become the leading region for national emissions induced by production of final good in Central region, also North West and South West region has a dramatic increase. **(2)** When looking at the share (the bottom part of Table 2), it's clear that, CO_2 emissions generated in inner-regional segment of domestic supply chains accounts for the majority of total induced CO_2 emissions for all regions except the North Municipalities. This can be easily understood since for most regions, their upstream supply chains are mainly located locally, while the upstream supply chain of the North Municipalities has a higher dependency on other regions. **(3)** However, the difference of the share across regions is still significant. For example, 29% of CO2 emissions in North Coast region, 34% of emissions in South Coast region and 40% emissions in East Coast region's production of final products are generated in extra-regional segment of domestic supply chains in 2007, and increase to 30%, 35% and 42% in 2010 respectively. This clearly reflects that the developed coastal regions' supply chains need more external intermediate inputs for producing final products, and much higher CO_2 emissions intensity is located in external segment of their domestic supply chain comparing to that of island regions.

3.2.2 Regional CO_2 emission inflow-outflow based on backward industrial linkage decomposition

In order to have a deep analysis on the backward industrial linkage based CO_2 emissions decomposition, we make a further decomposition by sectors that can help us to trace the CO_2 emissions at the detailed sector level in domestic supply chain in a particular region. EEX_B in Figure 10 shows how final demand on a specific goods generates a region's total CO_2 emissions (all sectors) by upstream DVC routes.

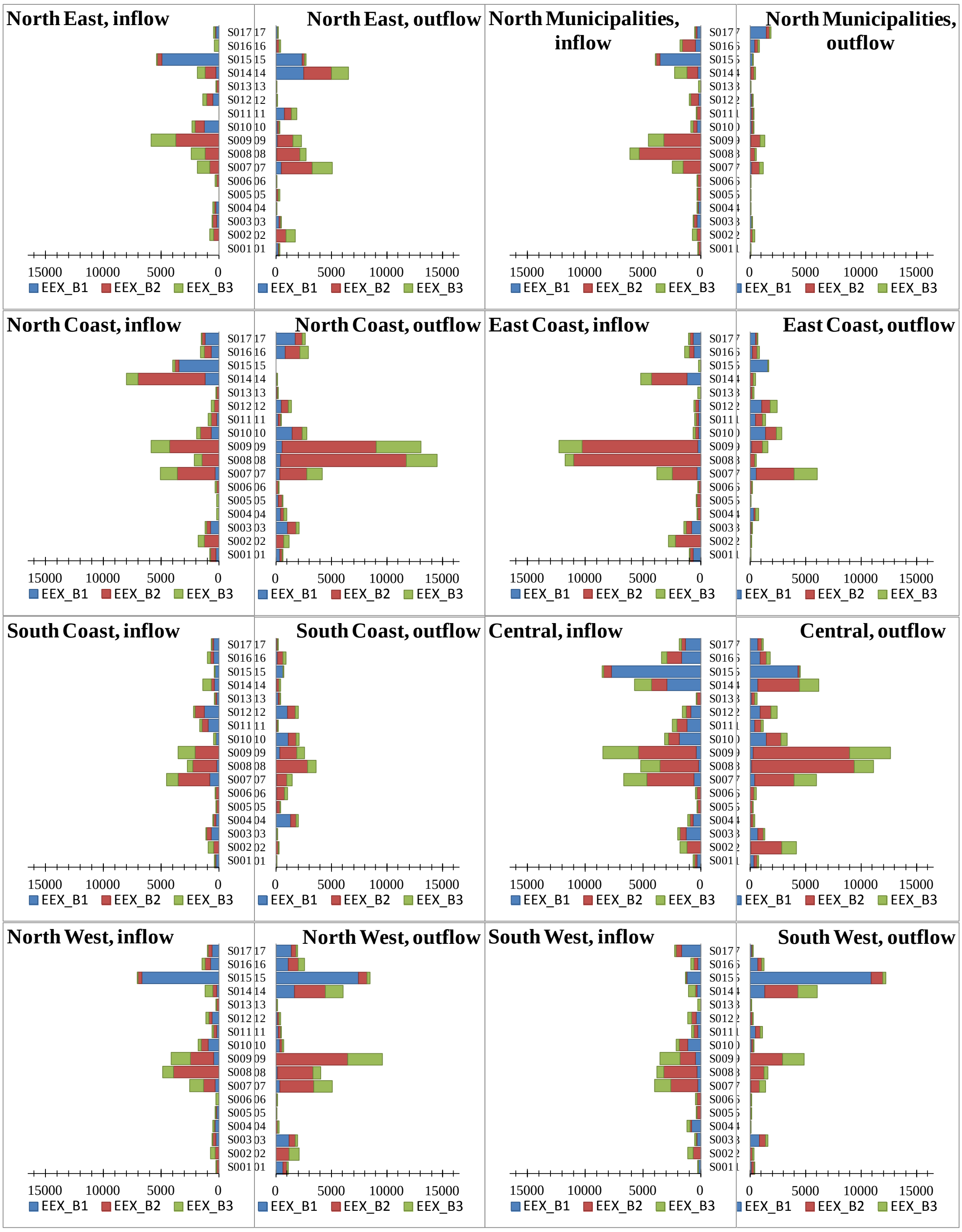


Figure 10 Regional CO2 emission inflow-outflow based on backward industrial linkage decomposition

The major features can be summarized as follows: (1) seeing from the inflow side, Sector 9 (Metal products), Sector 8 (Non-metallic mineral products) and Sector 7

(Chemicals and Chemical Products) are the main emitter for nearly all the regions, especially for the East Coast region, while the CO_2 emissions outflow of these sectors in North Coast region, North West region and Central region are much more than it in other regions, and main dominated by emissions in intermediate products. (2) It is interesting that CO_2 emissions embodied in final goods of Sector 15（Construction）in North West region and Central region is larger than other regions in both inflow side and outflow side, while South West region provide most CO_2 emissions outflow embodied in Sector 15' final goods (Construction). On the contrary, North East region, North Coast region and the North Municipalities are the main importer of Sector 15（Construction）'s CO_2 emissions with nearly little export of it. (3) The major emissions outflow in Sector 14(Electricity, gas, and water supply) are North East region, North West region, South West region and Central region. Meanwhile the East Coast region, North Coast region and Central region import more CO_2 emissions embodied in the Sector 14.

3.3 CO_2 emissions embodied in gross outflow

3.3.1 CO2 emissions induced by the production of gross exports for selected countries

As mention in the section 3, it is easy to identify who emits CO_2 emissions for whom to what extent in the production of gross outflow by the backward industrial linkage based decomposition technique. Table 4 represents the decomposition results for all regions for both 2007 and 2010. **(1)** At the absolute level, Central region gross outflow induce the largest amount of CO_2 emissions (74,6170 Kt) in 2010 followed by North Coast (63,9430 Kt) and North West region (55,9660 Kt). (2) When turning to look at the share of emissions, the total CO_2 emissions can be separated into inner-regional and extra-regional parts. The majority of induced CO_2 emissions in producing inter-regional exports are from the inner-regional side for all regions in both 2007 and 2010, except the North Municipalities (47% in 2010). (3) However, if a region has relatively large part of upstream production process in other regions in producing outflows, the share of extra-regional CO_2 emissions could be large, like the North Municipalities (53%), South Coast region (37%) and East Coast region (31%) in 2010. (4) Both inner-regional and extra-regional parts can be further divided into 4 parts (refer to Figure 4) that are based on different supply chain routes and types of final consumers. Apparently, the first three parts contribute more than the last parts in all regions. In 2010, the CO_2 emissions embodied in Central region's gross outflows are mainly for the direct importers' intermediate goods in the inner-regional side (45%), 16% is for fulfilling Central region's inter-regional trading partners' final demand who directly imports goods from Central region; 18% is for fulfilling third regions' final demand by providing intermediate goods to Central's inter-regional trading partners for their production of outflows to third regions; only 8% is for fulfilling Central its own final demand by inter-regional re-importing what has been "exported". For most regions, except South West region and the North Municipalities, their inner-regional CO2 emissions embodied in gross outflows is mainly through inter-regional trade in intermediate goods (part 2, 3, 4). For Part 4, the figure for the Central region is larger than the other regions. This is mainly because the Central region re-imports relative more its own intermediate goods outflows in domestic supply chains (refer to Figure 7, 8 10). As for the extra-regional parts, The North Municipalities shows the largest figure in which part 7and 8 accounts for 24% and 16%, respectively. This represents that 24% of the total CO_2 emissions embodied in the North Municipalities' gross outflows is from third regions who exports intermediate goods to North Municipalities for North Municipalities' further production of final goods export to North Municipalities' inter-regional trade partners; 16% of the total CO2 emissions embodied in North Municipalities' gross outflows is from third regions who exports intermediate goods to North Municipalities, then North Municipalities uses these goods to further produce intermediate goods and exports to North Municipalities' inter-regional trade partner for making final goods of the inter-regional trade partner. Part 5 shows the CO_2 emissions induced in the North Municipalities' trading partner regions who provide intermediate goods to North Municipalities for its production of final inter-regional exporting goods which finally consumed in its trading partner regions; part 6 shows the CO_2 emissions induce in North Municipalities' inter-regional trading partners who provide intermediate goods to North Municipalities for further process of intermediate outflows, which is imported by North Municipalities' trade partners regions for producing locally used final goods. Part 5 and part 6 account for only 8% and 5%, respectively, since this kind of feedback effect in domestic production networks is normally small.

Table 4 Inner and extra-regional CO2 emissions in the production of gross outflow--Backward industrial linkage based decomposition

	2007										
CO2 emissions (10KT)	Inner-regional CO2 emissions					Extra-regional CO2 emissions					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
North East	9,512	10,652	6,367	474	27,005	236	188	1,256	1,112	2,792	29,797
North Municipal	4,311	3,232	1,613	183	9,339	1,218	679	3,737	1,982	7,616	16,955
North Coast	7,607	18,259	8,327	2,746	36,939	602	841	2,401	4,372	8,216	45,155
East Coast	5,548	6,343	3,524	828	16,243	898	694	2,996	2,558	7,146	23,389
South Coast	5,970	6,831	2,589	434	15,824	922	698	4,208	3,775	9,603	25,427
Central	7,432	22,174	7,671	3,757	41,034	409	808	1,924	3,835	6,976	48,010
North West	13,315	15,391	7,718	768	37,192	808	339	2,985	1,796	5,928	43,120
South West	9,596	7,674	4,080	784	22,134	448	186	1,972	1,067	3,673	25,807
Share (%)	Inner-regional CO2 emissions					Extra-regional CO2 emissions					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
North East	32%	36%	21%	2%	91%	1%	1%	4%	4%	9%	100%
North Municipal	25%	19%	10%	1%	55%	7%	4%	22%	12%	45%	100%
North Coast	17%	40%	18%	6%	82%	1%	2%	5%	10%	18%	100%
East Coast	24%	27%	15%	4%	69%	4%	3%	13%	11%	31%	100%
South Coast	23%	27%	10%	2%	62%	4%	3%	17%	15%	38%	100%
Central	15%	46%	16%	8%	85%	1%	2%	4%	8%	15%	100%
North West	31%	36%	18%	2%	86%	2%	1%	7%	4%	14%	100%
South West	37%	30%	16%	3%	86%	2%	1%	8%	4%	14%	100%
	2010										
CO2 emissions (10KT)	Inner-regional CO2 emissions					Extra-regional CO2 emissions					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
North East	7,619	11,415	6,613	823	26,470	281	287	1,483	1,650	3,701	30,171
North Municipal	3,328	3,482	1,727	297	8,834	1,455	1,031	4,565	3,102	10,153	18,987
North Coast	8,750	28,312	11,461	3,386	51,909	802	1,412	2,968	6,852	12,034	63,943
East Coast	6,821	8,803	5,062	945	21,631	1,313	1,170	3,787	3,583	9,853	31,484
South Coast	5,749	9,326	3,782	462	19,319	958	980	4,315	5,092	11,345	30,664
Central	11,910	33,856	13,058	5,746	64,570	567	1,171	2,872	5,437	10,047	74,617
North West	15,134	20,506	9,852	1,505	46,997	1,177	568	4,418	2,806	8,969	55,966
South West	15,333	11,159	6,028	1,035	33,555	729	298	3,085	1,552	5,664	39,219
Share (%)	egional CO2 emissions in producing outflow p					egional CO2 emissions in producing outflow p					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
North East	25%	38%	22%	3%	88%	1%	1%	5%	5%	12%	100%
North Municipal	18%	18%	9%	2%	47%	8%	5%	24%	16%	53%	100%
North Coast	14%	44%	18%	5%	81%	1%	2%	5%	11%	19%	100%
East Coast	22%	28%	16%	3%	69%	4%	4%	12%	11%	31%	100%
South Coast	19%	30%	12%	2%	63%	3%	3%	14%	17%	37%	100%
Central	16%	45%	18%	8%	87%	1%	2%	4%	7%	13%	100%
North West	27%	37%	18%	3%	84%	2%	1%	8%	5%	16%	100%
South West	39%	28%	15%	3%	86%	2%	1%	8%	4%	14%	100%
	Between 2007 and 2010										
Chage rate of CO2 emisions	egional CO2 emissions in producing outflow p					egional CO2 emissions in producing outflow p					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
North East	-20%	7%	4%	74%	-2%	19%	53%	18%	48%	33%	1%
North Municipal	-23%	8%	7%	62%	-5%	19%	52%	22%	57%	33%	12%
North Coast	15%	55%	38%	23%	41%	33%	68%	24%	57%	46%	42%
East Coast	23%	39%	44%	14%	33%	46%	69%	26%	40%	38%	35%
South Coast	-4%	37%	46%	6%	22%	4%	40%	3%	35%	18%	21%
Central	60%	53%	70%	53%	57%	39%	45%	49%	42%	44%	55%
North West	14%	33%	28%	96%	26%	46%	68%	48%	56%	51%	30%
South West	60%	45%	48%	32%	52%	63%	60%	56%	45%	54%	52%
Chage rate of share (%)	egional CO2 emissions in producing outflow p					egional CO2 emissions in producing outflow p					Total
	part 1	part 2	part 3	part 4	subtotal	part 5	part 6	part 7	part 8	subtotal	
North East	-21%	6%	3%	71%	-3%	18%	51%	17%	47%	31%	
North Municipal	-31%	-4%	-4%	45%	-16%	7%	36%	9%	40%	19%	
North Coast	-19%	9%	-3%	-13%	-1%	-6%	19%	-13%	11%	3%	
East Coast	-9%	3%	7%	-15%	-1%	9%	25%	-6%	4%	2%	
South Coast	-20%	13%	21%	-12%	1%	-14%	16%	-15%	12%	-2%	
Central	3%	-2%	10%	-2%	1%	-11%	-7%	-4%	-9%	-7%	
North West	-12%	3%	-2%	51%	-3%	12%	29%	14%	20%	17%	
South West	5%	-4%	-3%	-13%	0%	7%	5%	3%	-4%	1%	

In order to investigate the structure change of gross outflows based CO_2 emissions between 2007 and 2010 across different routes, we calculate the change rate for both the absolute CO_2 emission figure and the corresponding share and show the results in the two bottom parts of Table 4. It is easy to see that: (1) the CO_2 emissions in gross outflows for all regions, experienced a rapid increase except North East region and the North Municipalities. The CO_2 emissions in gross outflows from the inner-regional parts face a decline by 2% and 5% in North East region and the North Municipalities, respectively. (2) When looking at the change of share, it is easy to see that the share of CO_2 emissions in inner-regional parts decreased for all regions, except Central region and South Coast region with a low growth rate at 1%. The share of extra-regional CO_2 emissions increased for most regions, except Central region and South Coast region. This indirectly reflects the fact that most regions are getting to use more intermediate inflows to produce their outflows. As a result, relatively more CO_2 emissions are induced externally rather than locally in producing outflows. (3) Looking at the changing pattern for part 3, part 7 and part 8, they have relatively large absolute share and also show almost positive change of their shares between 2007and 2010. All these three parts are related to the third regions effects in the decomposition. This implies the increasing complexity of specific route in domestic supply chains is often related to the increase of corresponding CO_2 emissions.

3.4 The potential environmental cost of interregional trade in value-added

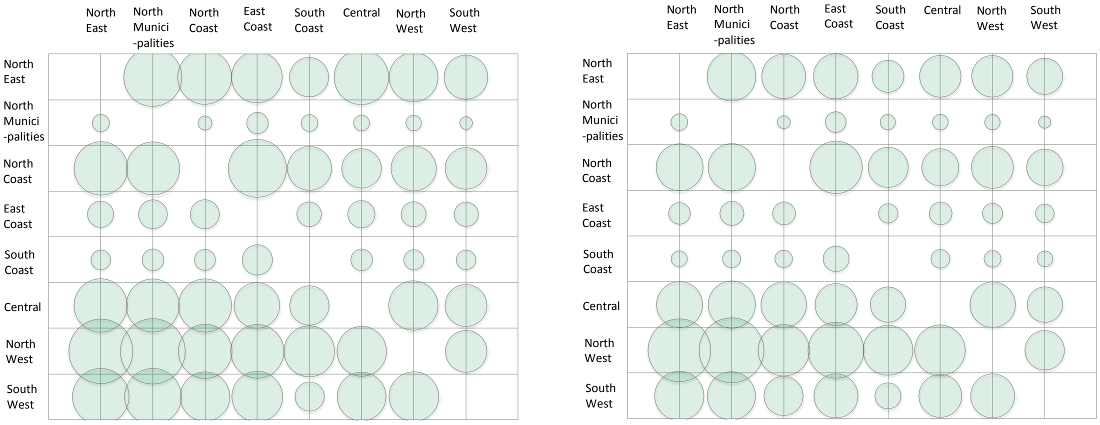
As mentioned in the third section, following the proposed decomposition frameworks, both value-added and embodied emissions can be traced at the same time. When dividing the induced value-added by induced CO_2 emissions, the potential environmental cost can be easily obtained. As an example, we apply this idea to the forward industrial linkage based decomposition (Figure 2) to show the relationship between trade in value-added and trade in CO_2 emissions. The main result is shown in Table 5 at the bilateral level. It can help us monitor the environmental cost when a region outflows value added to its partner region in detail. The estimation result covering all regions for both 2007 and 2010 can be clearly found in Figure 10. Obviously, the environmental cost of value-added outflows for North East region, North Coast region, Central region, North West region and South West region are relatively higher than other regions for both years. The cost decrease can be found for almost all regions except North West region during this 3 year period. At the region to region level, more variation of changing pattern can be observed. For example, one of the outstanding high-carbon interactions is East Coast region's outflows of value added to Central in 2007 declined by 20%, While, another outstanding high-carbon interactions from North West to the North Municipalities increased by 5%. The high-carbon trade flow from North West region to East Coast region increased by 11%, followed by high-carbon trade flow from North West region to Central region with 8% increase. In general, the environmental cost for producing inner-regional value added without inter-regional trade for all regions is lower than that of producing inner-regional value-added through inter-regional trade. This implies that the value-added gain by inter-regional trade may be through a high-carbon process, which indirectly reflects the fact of carbon leakage across regions due to trade.

Table 5 Trade in CO2 emissions/Trade in Value-added for 2007 and 2010

Unit: T/ 2007	Trade in CO2 emissions / Trade in Value-added								
	rth East	North Municipalities	th Coast	st Coast	th Coast	Central	rth West	uth West	Sum
North East		4.9	4.5	4.3	3.3	4.6	4.1	3.7	4.2
North Mu	1.4		1.2	1.8	1.4	1.3	1.3	1.1	1.3
North Coa	4.5	4.5		4.9	3.7	3.3	3.8	3.5	3.9
East Coas	2.2	2.4	2.4		2.1	2.3	2.1	2.0	2.2
South Coa	1.7	1.8	1.8	2.5		1.8	1.7	1.6	1.8
Central	4.5	4.4	4.5	3.8	3.3		4.1	3.5	3.9
North Wes	5.4	5.4	4.5	4.5	4.2	4.2		3.5	4.3
South Wes	4.7	4.8	4.2	4.3	2.5	4.1	4.2		3.8
Sum	3.4	4.3	3.0	3.9	2.9	3.1	3.1	2.6	3.2

2010	Trade in CO2 emissions / Trade in Value-added								
	rth East	North Municipalities	th Coast	st Coast	th Coast	Central	rth West	uth West	sum
North East		4.3	3.9	3.9	2.8	3.7	3.6	3.2	3.7
North Mu	1.5		1.1	1.8	1.3	1.4	1.4	1.1	1.3
North Coa	4.1	4.2		4.6	3.5	3.3	3.7	3.2	3.8
East Coas	1.9	2.1	2.0		1.7	2.0	1.8	1.6	1.9
South Coa	1.4	1.6	1.6	2.3		1.7	1.5	1.4	1.6
Central	4.1	4.2	4.0	3.7	3.1		4.0	3.1	3.7
North Wes	5.5	5.7	4.5	4.9	4.4	4.5		3.5	4.6
South Wes	4.3	4.3	3.5	3.9	2.3	3.8	3.9		3.6
Sum	3.3	4.0	2.9	3.8	2.7	2.9	3.0	2.4	3.1

	Change rate between 2007 and 2010 (%)								
	rth East	North Municipalities	th Coast	st Coast	th Coast	Central	rth West	uth West	sum
North East		−11%	−14%	−7%	−14%	−20%	−11%	−14%	−13%
North Mu	3%		−3%	2%	−5%	4%	4%	0%	0%
North Coa	−8%	−6%		−5%	−4%	−1%	−2%	−8%	−3%
East Coas	−13%	−12%	−17%		−17%	−12%	−15%	−19%	−14%
South Coa	−14%	−13%	−12%	−10%		−8%	−12%	−15%	−12%
Central	−9%	−6%	−10%	−3%	−5%		−3%	−11%	−5%
North Wes	3%	5%	1%	11%	4%	8%		0%	7%
South Wes	−8%	−11%	−17%	−9%	−6%	−8%	−7%		−6%
Sum	−2%	−7%	−2%	−3%	−7%	−6%	−3%	−7%	−4%



2007

2010

Figure 10 Trade in CO2 emissions/Trade in Value-added for 2007 and 2010

4. Policy Implication

The empirical results of this study have many policy implications. To make a clear understanding, we would like to address the policy suggestions through answering the four questions raised in the beginning of this paper.

(1) Carbon reduction policies on upstream regions and sectors

The analysis based on the forward industrial linkage decomposition both at regional and industrial level indicates how much emissions generated by a region if for its own final demand, for its downstream region's final goods demand, or for intermediate goods demand in the downstream DVCs routes. Therefore, carbon reduction policies should take the economic dependency between regions and sectors into consideration according to forward industrial linkage.

Upstream regions emissions reduction strategy: 1) refers to Figure 5, CO_2 emissions in production is mainly for the inner-regional final goods and service demand, especially for South West, North East and Central regions. These developing island regions are experiencing an urgent requirement for urbanization and economic development by extensive growth way. On the other hand, the lower energy efficiency due to the lack of low-carbon technology makes the situation even worse. Thus, how to make a balance between economic development and carbon emissions reduction is the mainly challenge for local governments. Due to the difficulty for reduce emissions amount immediately for this developing regions with great inner-demand, we suggest that greater investment from central government is needed to develop technologies for improving the efficiency of energy use in these regions. 2) For extra-regional demand, the CO_2 emissions embodied in intermediate outflow is the major contributor for Central and North West region, refers to Figure 7. It implies that these regions bear a large amount of emissions for their downstream regions, which is a result of inter-regional industry transfer. This process of industry transfer from developed regions to developing regions is primarily heavy and energy-intensive industry transfer, which is accompanied by the transfer of pollution and high carbon emissions. Therefore, these upstream regions (mainly island regions) low-income regions can no longer accept the heavy industry or energy-intensive industry transfer from the developed coastal regions (mainly island regions). To ensure that these industries are not transferred, local governments should set higher emission assessment criteria for new project investments. 3) Finally, the changing trend between 2007 and 2010 in these regions can provides some implications for dynamic control. Figure 6 shows the structure changes of demand in all regions, as mention above, the share of emissions for extra-regional demand in both North East and North West regions decline a lot, which gives an evidence for decreasing participation of DVCs of these two region. Meanwhile, if we divide the eight regions into three types of economies, and see the aggregated data of these regions in Figure 11 below, we find a gratifying progress that the carbon intensity for the intermediate inflows of Coastal regions (North Coast, East Coast and South coast) decrease, also the carbon intensity for both inner-regional final goods demand and intermediate outflows of North-Central regions become lower in 2010. In addition, we can also find a decline in the carbon intensity for EXX_F3 of Coastal regions. However, the carbon intensity for West regions (North West and South West) remains unchanged. In summary, the Coast regions import high-carbon intensity goods and export low-carbon intensity goods, while the North-Central regions and West regions trade in opposition way. The progress that North-Central regions have made indicates that North-Central regions have a better potential in carbon emission reduction than West regions. Thus, governments of West regions governments need do more effort in reducing carbon emissions intensity.

Upstream sector emissions reduction strategy: Sectoral decomposition of regional CO_2 emissions outflow and inflow provide enough evidence for making policies at sectoral level (refers to Figure 8). Sector 14 (Electricity, Gas and Water Supply), Sector 9 (Metal products), Sector 8 (Non-metallic mineral products) and Sector 7 (Chemicals and Chemical Products) accounts for the majority of the regional production based CO_2 emissions both inflow and outflow for all regions. This is not only because the emission intensity (refers to Figure 1) for these sectors is relatively high, but also their percentage as intermediate goods used in the domestic production network is also high. Therefore, emissions reduction should concentrate on these sectors, since there are huge amount of carbon emissions are embodied in products of these sectors and outflow to the downstream sectors as intermediate inputs in both source region and other regions. The introduction and development on low-carbon technology for chemicals, metal products and non-metallic mineral products pay an important role in reduce emissions from the upstream of DVCs.

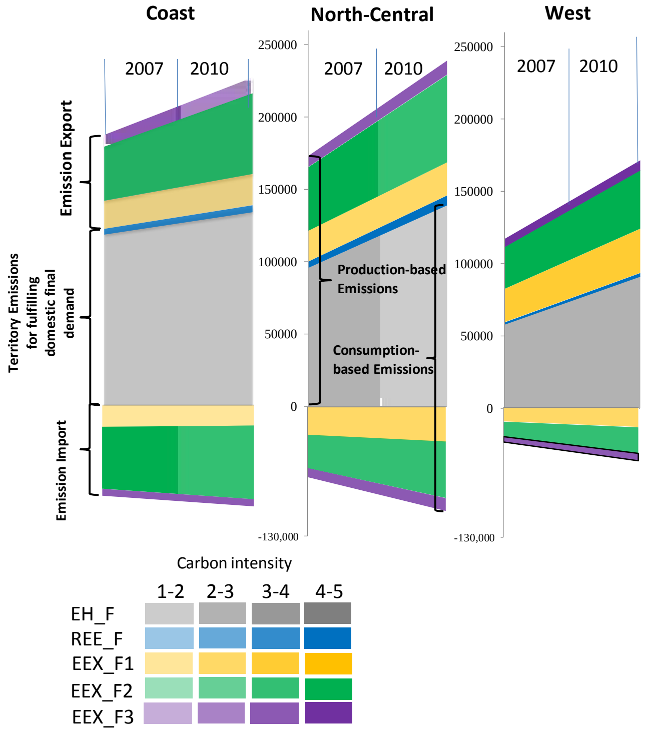


Figure 11 CO_2 emissions and carbon intensity by source of final demand in coastal, north-central and west regions

(2) Carbon reduction policies on downstream regions

Based on backward industrial linkage decomposition, we get a overview of domestic total CO_2 emissions to produce a region's final goods and service in both inner-regional and extra-regional segment of DVCs. The results shown in Figure 9 suggest that the developed coastal regions (North Coast, East Coast and South Coast regions) production of final products are generated in extra-regional segment of domestic supply chains increase to 30%, 35% and 42% in 2010 respectively. Thus, for these developed regions, the central government can carry out a pollutant cap control policy, since they have higher income, relative lower cost of environmental governance than island regions, and higher investment in technology development. Also, since the citizen environmental awareness in developed regions is higher than it in developing island, they have more willing to pay for environmental improvement. Moreover, the government of these regions should make policies to change the lifestyle of the citizen, encouraging the resource conservation and low-carbon lifestyle. In addition, these coastal regions may need to rely more on renewable energy sources by establishing a price mechanism to encourage the use of renewable energy, which will ensure an uninterrupted energy supply when traditional energy sources become scarcer.

(3) Carbon taxes based on emissions embodied in gross outflow (Who produce for whom?)

Carbon tax is a hot issue that has attracted a national wide discussion. When policy makers are trying to employ taxation (subsides), regulation to deal with the environment problems, undeveloped regions' aspirations for economic growth should also be considered and involved in the whole policy packages. In this study, we introduce the backward industrial linage decomposition on emissions in production of a region’s gross outflows. Here we make a comparison between domestic value chain participation degree and inner-region CO_2 emissions embodied in outflow in Figure 12. Obviously, the higher domestic value chain participation degree the region has, the lower inner-region CO_2 emissions embodied in outflow is. Apparently, the island regions will pay more carbon taxes than coastal regions due to the high carbon-intensity industry. However, if the policy effects of carbon taxes may show in a more complex way, for example, the island regions (North East, South West, North West and Central) can transfer their burden on carbon taxes to their direct import partner regions through embody the taxes fee in their products. On the other hand, the coastal regions and the North Municipalities with higher DVC participation degree may have a heavier burden on carbon taxes since they have a larger part of emissions embodied in extra-regional segment with higher import carbon intensity (the bubbles are darker). Consequently, to some extent, the carbon taxes can help to make a redistribution of carbon reduction responsibility in the way that the consumer region pays for the tax finally.

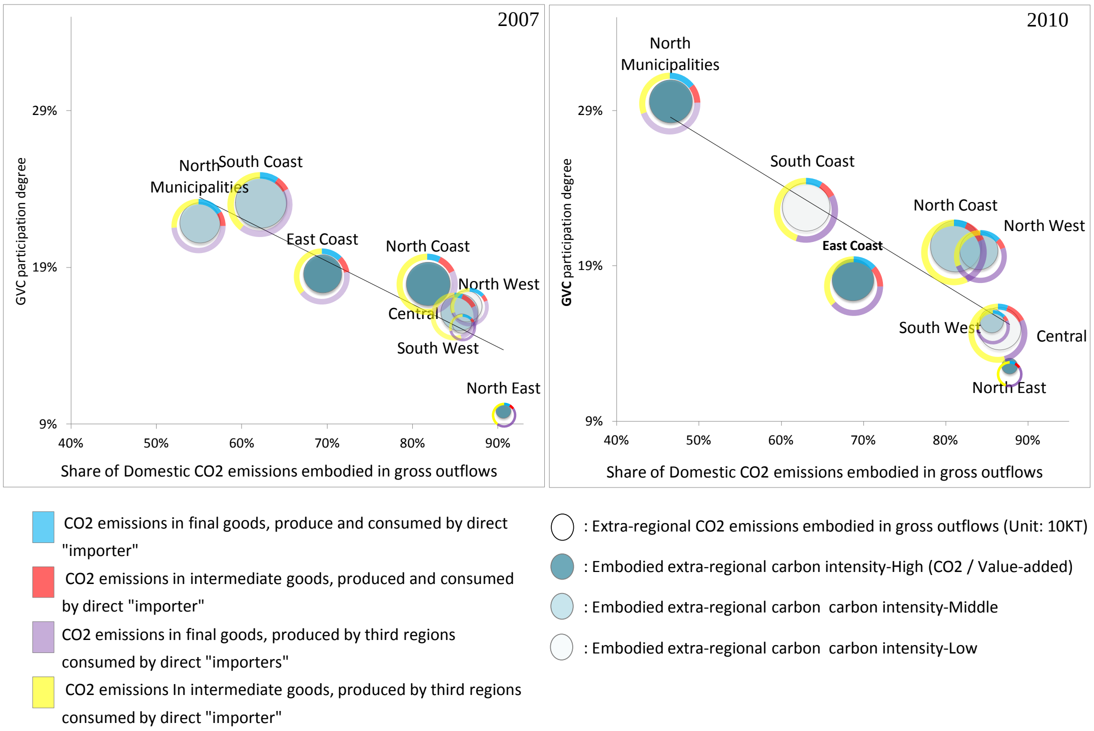


Figure 12 The relationship between domestic value chain participation degree and inner region CO_2 emissions embodied in outflow

(4) Carbon trading system based on potential environmental cost of interregional trade

The potential environmental cost of interregional trade of each region is provide in Figure 10. Actually, even most of the policy makers have realized the environmental cost in the economic development, environmental protection still gives way to economic growth in most regions. The carbon trading system can help to make this potential environmental cost become the real cost. For instance, the environmental cost of value-added outflows for North East region, North Coast region, Central region, North West region and South West region are relatively higher than other regions for both years. With the carbon trading system, if these regions want to obtain more emission quota, they should pay for the extra emission quota. Thus, carbon trading system could incentive regions with high emissions to reduce their emissions in order not to pay for the extra emission quota.

6. Concluding remarks

This paper analyzes the creation and distribution pattern of CO2 emissions in China's domestic-interregional value chains. The motivation of this paper is from recent literature that emphasizes the important role that domestic value chain plays in analysis on China's regional carbon emissions. Compared with previous studies, the main feature of this study is borrow the idea presented in the recent innovative works by Meng, Peters and Wang (2014) to trade CO2 emissions in China's domestic value chains at regional, industrial, product and bilateral (interregional) levels.

The main findings of this study based on the downstream oriented (forward industrial linkage) decomposition: (1) For all regions and for both years, the CO_2 emission generated by the production of local produced goods and services that sale directly at local market account for the majority of the total emissions. (2) The share of CO_2 emissions generated by the production of intermediate outflow absorbed by the direct "import" region contribute the largest share of CO_2 emissions generated by the products consumed in other regions. (3) The changes in shares of CO_2 emissions shows three patterns: "increase in CO_2 emissions shares for inner-regional demand and decrease in CO_2 emissions shares for extra-regional demand" (the North Municipalities, North East region and North West region"; "Decrease in CO_2 emissions shares for inner-regional demand and increase in CO_2 emissions shares for extra-regional demand"(see North Coast region, East Coast region and South Coast region); "Increase in emissions shares for both inner-regional and extra-regional demand"(for instance, the shares of emissions of Central region and South West region). (4)Sector 14 (Electricity, Gas and Water Supply), Sector 9 (Metal products), Sector 8 (Non-metallic mineral products) and Sector 7 (Chemicals and Chemical Products) accounts for the majority of the regional production based CO_2 emissions both inflow and outflow in all regions. (5) The environmental cost of value-added outflows for North East region, North Coast region, Central region, North West region and South West region are relatively higher than other regions for both years. The cost decrease can be found for almost all regions except North West region during this 3 year period.

The main findings of this study based on the upstream oriented (backward industrial linkage) decomposition: (1) At the absolute level, East Coast region and Central region's production of final products no matter they are used locally or externally generates massive amount of total domestic CO_2 emissions followed by North Coast in both 2007 and 2010. **(2)** CO_2 emissions generated in inner-regional segment of domestic supply chains accounts for the majority of total induced CO_2 emissions for all regions except the North Municipalities. (3) At the absolute level, Central region gross outflow induce the largest amount of CO_2 emissions in 2010 followed by North Coast and North West region. (3) The majority of induced CO_2 emissions in producing inter-regional exports are from the inner-regional side for all regions in both 2007 and 2010, except the North Municipalities (47% in 2010). (4) The share of extra-regional CO_2 emissions in the North Municipalities, South Coast region and East Coast region for producing outflows are larger than other regions. (5) The CO_2 emissions in gross outflows for all regions experienced a rapid increase except North East region and the North Municipalities. (6) When looking at the change of share, it is easy to see that the share of CO_2 emissions in inner-regional parts decreased for all regions, except Central region and South Coast region with a low growth rate at 1%. (6) The increasing complexity of specific route in domestic supply chains is often related to the increase of corresponding CO_2 emissions.

Main policy implications based on the empirical studies: (1) greater investment from central government is needed to develop technologies for improving the efficiency of energy use in the island regions (South West, North East, North West and Central regions); (2) these island regions can no longer accept the heavy industry or energy-intensive industry transfer from the developed coastal regions (North Coast, East Coast and South Coast). To ensure that these industries are not transferred, local governments should set higher emission assessment criteria for new project investments; (3) the introduction and development on low-carbon technology for chemicals, metal products and non-metallic mineral products pay an important role in reduce emissions from the upstream of DVCs. (4) for coastal regions (North Coast, East Coast and South Coast), the central government can carry out a pollutant cap control policy, (5) the government of coastal regions should make policies to change the lifestyle of the citizen, encouraging the resource conservation and low-carbon lifestyle; (6) these coastal regions may need to rely more on renewable energy sources by establishing a price mechanism to encourage the use of renewable energy, which will ensure an uninterrupted energy supply when traditional energy sources become scarcer. (7) to some extent, the carbon taxes can help to make a redistribution of carbon reduction responsibility by transfer it to their trading partner regions through inter-regional trade. (8) The carbon trading system can help to make the potential environmental cost become the real cost, which could incentive regions with high emissions to reduce their emissions in order not to pay for the extra emission quota.

Appendix

Table A1

Eight regions	31 provincial level divisions
Northeast	Liaoning, Jilin, Heilongjiang
North Municipalities	Beijing, Tianjin
North coast	Hebei, Shandong
East coast	Shanghai, Jiangsu, Zhejiang
South coast	Fujian, Guangdong, Hainan
Central	Shanxi, Anhui, Jiangxi, Henan, Hubei, Hunan
Northwest	Inner Mongolia, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang
Southwest	Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet

References

[1]. Ang, B.W., (1999). Is the energy intensity a less useful indicator than the carbon factor in the study of climate change? Energy Policy 27, 943-946.

[2]. Auffhammer, M., Carson, R.T., (2008). Forecasting the path of China's CO2 emissions using province-level information. Journal of Environmental Economics and Management 55, 229-247.

[3]. Ahmad, H., Wyckoff, A.W. (2003). Carbon dioxide emissions embodied in international trade of goods. STI Working Paper 2003/15. OECD.

[4]. Chang, C.C., (2010). A multivariate causality test of carbon dioxide emissions, energy consumption and economic growth in China. Applied Energy 87, 3533-3537.

[5]. Feng, K.S., Hubacek, K., Guan, D.B., (2009). Lifestyles, technology and COz emissions in China: a regional comparative analysis. Ecological Economics 69, 145 一 154.

[6]. Grossman, G.M., Krueger, A.B., (1995). Economic growth and the environment. Quarterly Journal of Economics 112, 353-378.

[7]. Guo, J., Zou, L.L., Wei, Y.M., (2010). Impact of inter-sectoral trade on national and global COz emissions: an empirical analysis of China and US. Energy Policy 38, 1389-1397.

[8]. Hausman, J.A., 1978. Specification tests in econometrics. Econometrica 46, 1251-1271.

[9]. Hausman, J.A., Taylor, W.E., (1981). Panel data and unobservable individual effects. Econometrica 49, 1377-1398.

[10]. Hoen, A.R., Oosteraven, J. (2006). On the measurement of comparative advantage. The Annals

[11]. IEA, (2010). CO2 emissions from fuel combustion 2010-highlights.<http: //www.iea.org/publications/free-new-Desc.asp?PUBS-ID=2143>.

[12]. IPCC, (2006). The 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 Guidelines). <http://www.ipcc-nggip.iges.or.jp/public/2006g1/index.html>.

[13]. Jalil, A., Mahmud, S.F., (2009). Environment Kuznets curve for CO2 emissions: a cointegration analysis for China. Energy Policy 37, 5167-5172.

[14]. Koopman, R., Wang, Z., Wei, S.J. (2014). Tracing Value-Added and Double Counting in Gross Exports. American Economic Review, 104(2), pp. 459-94.

[15]. Lenzen, M., Pade, L.L., Munksgaard, J. (2004). CO2 multipliers in multi-region input-output models. Economic Systems Research, 16(4), pp. 391-412.

[16]. Lenzen, M., Moran, D, Kanemoto, K., Foran, B., Lobefaro, L., Geschke, A. (2012), International trade drives biodiversity threats in developing nations, Nature, 486.

[17]. Lenzen, M., Murray, J., Sack, F., Wiedmann, T. (2007). Shared producer and consumer responsibility – theory and practice. Ecological Economics, 61, pp27-42.

[18]. Leontief, W. (1936). Quantitative input and output relations in the economic system of the United States. The Review of Economic and Statistics, 18, pp. 105-25.

[19]. Liang, Q.M., Fan, Y., Wei, Y.M., (2007). Multi-regional input-output model for regional energy requirements and COz emissions in China. Energy Policy 35, 1685 一 1700.

[20]. Lin, B.q，Sun, C.W., 2010. Evaluating carbon dioxide emissions in international trade of China. Energy Policy 38, 613-621.

[21]. Lin, S.J., Lu, LJ., Lewis, C., (2006). Identifying key factors and strategies for reducing industrial COz emissions from a non-Kyoto protocol member's (Taiwan) perspective. Energy Policy 34, 1499-1507.

[22]. Lin, J., Pan, D., Davis, S.J., Zhang, Q., He, K., Wang, C., Streets, D.G., Wuebbles, D.J., Guan, D. (2014). China’s international trade and air pollution in the united States. PNAS, 111(5), pp.1736-1741.

[23]. Liu, X.B., Ishikawa, M., Wang, C., Dong, Y.L., Liu, W.L., (2010). Analyses of CO2 emissions embodied in Japan-China trade. Energy Policy 38, 1510-1518.

[24]. Meng, L., Guo, J., Chai, J., Zhang, Z., (2011). China’s regional CO2emissions: characteristics, inter-regional transfer and emission reduction policies. Energy Policy 39, 6136–6144.

[25]. Meng, B., Wang, Z., Koopman, R. (2013). How are global value chains fragmented and extended in China’s domestic production networks? IDE Discussion Paper, 424.

[26]. Meng, B., Peters, G.P., Wang, Z. (2014). Tracing CO2 emissions in global value chains, USITC Working Paper. 2104-12A.

[27]. Narayan, P.K., Narayan, S., (2010). Carbon dioxide emissions and economic growth: panel data evidence from developing countries. Energy Policy 38, 661-666.

[28]. Peters, G.P. (2008). From production-based to consumption-based national emission inventories. Ecological Economics 65, pp. 13-23.

[29]. Peter, G.P., Hertwich, E.G. (2008a). CO2 embodied in international trade with implications for global climate policy. Environmental Science and Technology, 42 (5), pp. 155-181.

[30]. Peter, G.P., Hertwich, E.G. (2008b). Post-Kyoto greenhouse gas inventories: production versus consumption. Climatic Change, 86, pp. 51-66.

[31]. Peter, G.P., Minx, J.C., Weber, C.L., Edenhofer, O. (2008). Growth in emission transfers via international trade from 1990 to 2008. PNAS.

[32]. Roca, J., Alcantara, V., (2001). Energy intensity, COz emissions and the environmental Kuznets curve: the Spanish case. Energy Policy 29, 553-556.

[33]. Wang, Z., Wei, S.J., Zhu, K. (2013). Quantifying international production sharing at

the bilateral and sector levels. NBER Working Paper No. 19677.

[34]. Wiedmann, T., Lenzen, M., Turner, K., Barret, J. (2007). Examining the global environmental impact of regional consumption activities － Part2: Review of input-output models for the assessment of environmental impacts embodied in trade. Ecological Economics, 61, pp15-26

[35]. Wiedmann, T. (2009). A review of recent multi-region input-output models used for consumption-based emission and resource accounting. Ecological Economics, 69, pp.211-222.

[36]. Sato, M. (2012). Embodied carbon in trade: a survey of the empirical literature. CCCEP Working paper, 89.

Chapter 3

Production Sharing, Demand Spillovers and CO_2 Emissions: The Case of Chinese Regions in GVCs

Jiansuo PEI[a], Bo MENG[b], Fei WANG[a] and Jinjun XUE[c]

Abstract: Recent trade literature highlights production sharing among economies (e.g., Johnson and Noguera, 2012; Koopman et al., 2014), and some studies report that 20%-25% of CO_2 emissions can be attributed to international trade (e.g., Peters et al., 2011). However, the mechanism explaining how and to what extent production sharing affects CO_2 emissions remains unclear. This study, as an extension of Meng et al. (2013a), adopts the perspective of demand spillovers to provide new insights regarding the position of Chinese domestic-regions' production in global value chains (GVCs) and their associated CO_2 emissions. To this end, we constructed a new type of World Input-Output Database (WIOD) in which China's domestic interregional input-output table for 2007 is endogenously embedded. The pattern of China's regional demand spillovers across both domestic regions and countries is revealed by employing this new database. These results were then connected to endowments theory, which helps to make sense of the empirical results. It is found that China's regions are located relatively upstream in GVCs, and had CO_2 emissions in net exports, which were entirely predicted by the environmental extended HOV model. Our study points to micro policy instruments to combat climate change: for example, tax reform for energy inputs that helps to change the production pattern, which then has an impact on trade patterns and so forth.

Keywords: Production sharing; CO_2 emissions; demand spillovers; global value chains

JEL Codes: R15; C65; Q56

a.University of International Business and Economics, China; b. Institute of Developing Economies, IDE-JETRO, Japan; c. Nagoya University, Japan

1. Introduction

Today's economy is characterized by the increasing fragmentation of international production, where production sharing is the norm rather than an exception (see Johnson and Noguera, 2012; Koopman et al., 2014). This has two implications. First, intermediate goods cross borders multiple times before they are consumed by final users, meaning that increasing amounts of final goods are "Made in the World" (see WTO-IDE, 2011, and OECD-WTO, 2012) and that global value chains (GVCs) matter. Second, production-based accounting principles (say, the methods proposed in the Kyoto Protocol) for greenhouse gas (GHG) emissions, such as carbon dioxide (CO_2) emissions, face an increasing challenge. Along with the availability of better datasets, it is possible to use alternative methods to account for CO_2 emissions according to different end-users, so that producer responsibility and consumer responsibility are distinguished (see e.g., Peters, 2008).

In fact, previous studies have tackled the problem of CO_2 emissions embodied in trade (exports, imports or both) and have reached a consensus about the latest developments (Peters and Hertwich, 2008; Peters et al., 2011). Specifically, the increase of CO_2 emissions embodied in trade seen over the last couple of years coincided with the ratification of Kyoto Protocol. However, the pattern of CO_2 emissions embodied in trade among economies and, in particular, the mechanism for their growth remains to be explained.[1] According to standard trade theory, more specialized production is usually accompanied by a larger amount of output from all relevant trading partners. It is

---

[1] Copeland and Taylor (2003) present a nice review of related literature. Temurshoev (2006) explicitly tests the "pollution haven hypothesis" and the "factor-endowment hypothesis". However, the problem of the pattern of CO_2 emissions embodied in trade and its origins has not been tackled.

therefore possible that production sharing will increase CO_2 emissions due to an overall growth in production. In the meantime, industry share structure may change, which may or may not contribute to CO_2 emissions. Equally important is that, due to growing output, production technology may improve (and thus the CO_2 emission intensity may fall). These effects are called the scale effect, the composition effect, and the technology effect in the literature (see Grossman and Krueger, 1993; Levinson, 2009). Consequently, the relationship between production sharing and CO_2 emissions is unclear, which calls for a more general framework as well as empirical investigation. So, our first research question is what determines the pattern of CO_2 emissions embodied in trade among economies?

In 2013, China’s total merchandise trade volume surpassed that of the United States and reached 4 trillion US dollars, making China the largest trading economy. China is the subject of intense debate about whether she should be held accountable for total CO2 emissions “on behalf of other economies that import goods from China” (see Weber et al., 2008; Dietzebacher et al., 2012). At the same time, data from the National Bureau of Statistics show that significant heterogeneity exists in regions within China, in terms of gross regional product (GRP), regional energy input intensity in production and so forth. For example, in 2013, the GRP ranged from 80.7 billion RMB (Yuan) in Tibet to 6.2 trillion Yuan in Guangdong Province. The energy input intensity difference in production is also substantial. Defined as tons of equivalent coal input per 10,000 Yuan of output, it ranged from 0.46 in Beijing to 2.28 in Ningxia Province in 2011.

On the other hand, interregional trade and production sharing among China’s regions further highlight the importance of CO_2 emissions accounting in the context of GVCs. To motivate this idea, suppose there is falling external demand in the Chinese

Coastal region due to a financial crisis. This shock drives down the relevant output in the Coastal region, and because some raw materials or intermediate inputs come from other regions in China, output will also contract in those regions. This is the phenomenon of demand spillover (see also Bems et al., 2010).

Similarly, CO2 emissions are embodied in interregional trade as well. More importantly, production sharing is even more pronounced among domestic regions than at international level. Meng et al. (2013a) made one of the first attempts to account for regional production sharing and the domestic interregional flow of CO_2 emissions (see also Liu et al., 2012; Qi et al., 2013; Feng et al., 2013 among others), but these studies did not fully link the domestic production chains with international production chains, thus missing one important component in the context of GVCs. In the existing literature, China's regional exports and imports are treated as exogenous rather than endogenous variables. To fill this gap in this line of study, here we utilize a novel dataset (Meng et al., 2013b) that China's domestic regions within an international input-output database. This enables us to provide a link between domestic production relationships and international production fragmentation.

To summarize, in this paper we employ a novel dataset that enables us to address the question of regional CO_2 emissions in the context of GVCs and extends the work of Meng et al. (2013a). To facilitate our analysis, the methodology of Serreno and Dietzenbacher (2010) is adopted, and more importantly, an environmental extended HOV model is employed. In so doing, we can put the results in a theoretically consistent framework and make sense of the empirical findings. Our results are relevant for policy discussions in general and, in particular, for China's Emissions Trading System (ETS) and other regional policies combating climate change.

As a first impression, China's four regions all run a surplus of CO_2 emissions in net export vis-à-vis overseas trading partners. Furthermore, upstream regions tend to be net exporters of CO_2 emissions. More interestingly, if the pattern is analyzed within the framework of the environmental extended HOV model, the direction of net CO_2 emissions flows can be entirely predicted. We suspect that this result also holds for other pollutants in a very general sense. If this is the case, it seems to suggest a resolution to the debate of "pollution haven hypothesis" vs. "factor-endowment hypothesis", as the factor endowment is the ultimate determinant of trade pattern (whether the trade is in factor content or pollutants).

The remainder of the paper is structured as follows. Section 2 presents the new methodology for the estimation of factor content of trade (and also of emissions embodied in trade) and the environmental extended HOV model. The section that follows gives a brief introduction of the construction of the novel dataset. Section 4 provides stylized facts and empirical results. The last section contains our conclusions.

2. Methodology

In this section, we develop the methodology of Meng et al. (2013a) in two respects. First, following Serrano and Dietzenbacher (2010), a demand-driven perspective is adopted, which is in the spirit of the Leontief production function.[1] Second, the extended environmental endowments theory is incorporated. By doing so, we can present richer predictions.

2.1 Modeling a full interregional input-output matrix

As shall be made clear in the data section, our novel dataset covers four regions within China along with other major economies and rest of the world (ROW). To keep

---

[1] Similar applications are found in the study of global value chains (GVCs): see Timmer et al. (2013, 2014).

things simple, the four regions within China are also considered as distinct regions. In this sense, the dataset is a full interregional input-output matrix, consisting of eight regions (including ROW).

Now we are in a position to give a formal formulation of key elements. As a starting point, consider two regions, one called Home (indexed by 1) and the other named Foreign (indexed by 2). Each region has its own production technology, endowments and pollutants. Further, it is assumed that each region has *n* production sectors, and each sector produces one single product (i.e., pure sectors). Each product can be used as intermediate goods either in its own region or in the other region; it can also enter into final uses, such as consumption or investment, both in its own region and in the other region. Using matrices, we can formulate the idea as[1]

$$\begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \end{pmatrix} = \begin{bmatrix} \mathbf{A}^{11} & \mathbf{A}^{12} \\ \mathbf{A}^{21} & \mathbf{A}^{22} \end{bmatrix} \begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \end{pmatrix} + \begin{pmatrix} \mathbf{y}^{11} + \mathbf{y}^{12} \\ \mathbf{y}^{21} + \mathbf{y}^{22} \end{pmatrix} \tag{1a}$$

or in compact form as

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \tag{1b}$$

where $\mathbf{A}^{11}$ and $\mathbf{A}^{22}$ are intra-regional input coefficients,[2] while $\mathbf{A}^{12}$ and $\mathbf{A}^{21}$ are inter-regional input coefficients that give an indication of the extent of production fragmentation. Likewise, $\mathbf{y}^{11}$ and $\mathbf{y}^{22}$ represent final uses of local production, while

---

[1] As a convention, a matrix is denoted by a bold capital letter, a (column) vector by a bold lower-case letter and a scalar by a normal weight lower-case letter. A row vector is obtained via the transposition of a column vector, and is indicated by a prime. A diagonal matrix is represented with a hat and has the elements of a vector along the main diagonal and zeros elsewhere.

[2] It is worth noting that input coefficients are different from technical coefficients. They have different interpretations and thus have different uses. Input coefficients depict local inter-industry linkages, whereas technical coefficients give the technological structure (irrespective of whether items are sourced from within the region or from imports). Essentially, the latter term is suitable when discussing technological changes; in contrast, the former term is useful when addressing local direct and indirect impacts, which is just the issue we tackle here.

$\mathbf{y}^{12}$ and $\mathbf{y}^{21}$ represent goods imported to fulfill final demand. Finally, $\mathbf{x}^{1}$ and $\mathbf{x}^{2}$ are total outputs of region 1 and region 2, respectively. Rearranging equation 1a (and equation 1b), we get

$$\begin{pmatrix} \mathbf{x}^{1} \\ \mathbf{x}^{2} \end{pmatrix} = \left(\mathbf{I} - \begin{bmatrix} \mathbf{A}^{11} & \mathbf{A}^{12} \\ \mathbf{A}^{21} & \mathbf{A}^{22} \end{bmatrix} \right)^{-1} \begin{pmatrix} \mathbf{y}^{11} + \mathbf{y}^{12} \\ \mathbf{y}^{21} + \mathbf{y}^{22} \end{pmatrix} = \begin{bmatrix} \mathbf{L}^{11} & \mathbf{L}^{12} \\ \mathbf{L}^{21} & \mathbf{L}^{22} \end{bmatrix} \begin{pmatrix} \mathbf{y}^{11} + \mathbf{y}^{12} \\ \mathbf{y}^{21} + \mathbf{y}^{22} \end{pmatrix} \tag{2a}$$

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{L}\mathbf{y} \tag{2b}$$

where, $\mathbf{L} \equiv (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix.

In order to estimate the CO_2 emissions associated with each region's production, $\boldsymbol{\mu}^{r}$ is defined as the emissions intensity (*r* = Home, Foreign), with a typical element μ_j^r indicating the amount of CO_2 emissions associated with the production of one unit total output in sector *j* (*j* = 1, …, n) in region *r*. Thus, CO_2 emissions in each region can be formulated as

$$\begin{pmatrix} \mathbf{e}^{1} \\ \mathbf{e}^{2} \end{pmatrix} = \begin{pmatrix} \hat{\boldsymbol{\mu}}^{1}\mathbf{x}^{1} \\ \hat{\boldsymbol{\mu}}^{2}\mathbf{x}^{2} \end{pmatrix} = \begin{bmatrix} \hat{\boldsymbol{\mu}}^{1}\mathbf{L}^{11} & \hat{\boldsymbol{\mu}}^{1}\mathbf{L}^{12} \\ \hat{\boldsymbol{\mu}}^{2}\mathbf{L}^{21} & \hat{\boldsymbol{\mu}}^{2}\mathbf{L}^{22} \end{bmatrix} \begin{pmatrix} \mathbf{y}^{11} + \mathbf{y}^{12} \\ \mathbf{y}^{21} + \mathbf{y}^{22} \end{pmatrix} = \begin{bmatrix} \mathbf{E}^{11} & \mathbf{E}^{12} \\ \mathbf{E}^{21} & \mathbf{E}^{22} \end{bmatrix} \begin{pmatrix} \mathbf{y}^{11} + \mathbf{y}^{12} \\ \mathbf{y}^{21} + \mathbf{y}^{22} \end{pmatrix} \tag{3}$$

where, $\mathbf{E}^{rs}$ with its typical element e_j^{rs} gives region *r*'s emissions due to the final demand (both intra- and inter-regional) for product *j* from region *r*.

Intuitively, we can split equation (3) into two equations, in which the production-based accounting principle (see equation (3a)) and the consumption-based accounting principle (see equation (3b)) are explicitly distinguished (see Dietzenbacher et al., 2012). Following the production-based accounting principle, only the producers are held accountable for any emissions associated with the production process; in contrast, following the consumption-based accounting principle, consumers are held responsible for emissions as they consume goods.

$$\begin{pmatrix} \mathbf{e}_p^1 \\ \mathbf{e}_p^2 \end{pmatrix} = \begin{pmatrix} \mathbf{e}^1 \\ \mathbf{e}^2 \end{pmatrix} = \begin{bmatrix} \hat{\boldsymbol{\mu}}^1\mathbf{L}^{11} & \hat{\boldsymbol{\mu}}^1\mathbf{L}^{12} \\ \hat{\boldsymbol{\mu}}^2\mathbf{L}^{21} & \hat{\boldsymbol{\mu}}^2\mathbf{L}^{22} \end{bmatrix} \begin{pmatrix} \mathbf{y}^{11}+\mathbf{y}^{12} \\ \mathbf{y}^{21}+\mathbf{y}^{22} \end{pmatrix} = \begin{bmatrix} \mathbf{E}^{11} & \mathbf{E}^{12} \\ \mathbf{E}^{21} & \mathbf{E}^{22} \end{bmatrix} \begin{pmatrix} \mathbf{y}^{11}+\mathbf{y}^{12} \\ \mathbf{y}^{21}+\mathbf{y}^{22} \end{pmatrix} \tag{3a}$$

$$\begin{pmatrix} \mathbf{e}_c^1 \\ \mathbf{e}_c^2 \end{pmatrix} = \begin{pmatrix} (\hat{\boldsymbol{\mu}}^1\mathbf{L}^{11}+\hat{\boldsymbol{\mu}}^2\mathbf{L}^{21})\mathbf{y}^{11}+(\hat{\boldsymbol{\mu}}^1\mathbf{L}^{12}+\hat{\boldsymbol{\mu}}^2\mathbf{L}^{22})\mathbf{y}^{21} \\ (\hat{\boldsymbol{\mu}}^1\mathbf{L}^{11}+\hat{\boldsymbol{\mu}}^2\mathbf{L}^{21})\mathbf{y}^{12}+(\hat{\boldsymbol{\mu}}^1\mathbf{L}^{12}+\hat{\boldsymbol{\mu}}^2\mathbf{L}^{22})\mathbf{y}^{22} \end{pmatrix} = \begin{pmatrix} (\mathbf{E}^{11}+\mathbf{E}^{21})\mathbf{y}^{11}+(\mathbf{E}^{12}+\mathbf{E}^{22})\mathbf{y}^{21} \\ (\mathbf{E}^{11}+\mathbf{E}^{21})\mathbf{y}^{12}+(\mathbf{E}^{12}+\mathbf{E}^{22})\mathbf{y}^{22} \end{pmatrix} \tag{3b}$$

Both methods have their own uses. As most statistics are production unit based, it is relatively easy and straightforward to obtain relevant data. However, if Home has relatively stringent environmental laws, it is expected that firms may shift to Foreign for production, a phenomenon called the “pollution haven hypothesis” in the literature (see Copeland and Taylor, 2003, for a nice review). In this regard, the consumption-based accounting principle can be an effective alternative to allocate responsibility for emissions (and other pollutants).

2.2 CO_2 emissions embodied in trade

As an accounting identity, CO_2 emissions are the same irrespective of whether a production-based accounting principle or a consumption-based accounting principle is adopted. Clearly, for our hypothetical world with two regions, one region’s net CO_2 emissions embodied in trade equals the other’s net CO_2 emissions embodied in trade (with opposite signs). To facilitate our analysis, take Home region (region 1) as an example. The CO_2 emissions embodied in exports and in imports need to be separately estimated.

First we consider exports:

$$\mathbf{e}_{ex}^1 = (\mathbf{E}^{11}+\mathbf{E}^{21})\mathbf{y}^{12} + \mathbf{E}^{12}(\mathbf{y}^{21}+\mathbf{y}^{22}) \tag{4}$$

Equation (4) gives CO_2 emissions embodied in exports. Here, we distinguish between final uses and intermediate inputs. Specifically, $(\mathbf{E}^{11}+\mathbf{E}^{21})\mathbf{y}^{12}$ represents the

(Home and Foreign) emissions embodied in Home's export of final goods $\mathbf{y}^{12}$ to Foreign; while $\mathbf{E}^{12}(\mathbf{y}^{21}+\mathbf{y}^{22})$ gives emissions embodied in Home's exports of intermediate goods to Foreign, noting that the intermediate goods are used for the satisfaction of final consumption in both regions (i.e., ($\mathbf{y}^{21}+\mathbf{y}^{22}$)).

In the same fashion, Home's emissions in embodied imports can be expressed as

$$\mathbf{e}_{im}^{1}=(\mathbf{E}^{22}+\mathbf{E}^{12})\mathbf{y}^{21}+\mathbf{E}^{21}(\mathbf{y}^{11}+\mathbf{y}^{12}) \qquad (5)$$

Hence, Home's balance of emissions embodied in trade can be calculated as emissions embodied in exports net of emissions embodied in imports.

$$\mathbf{teb}^{1}=\mathbf{E}^{11}\mathbf{y}^{12}+\mathbf{E}^{12}\mathbf{y}^{22}-\mathbf{E}^{22}\mathbf{y}^{21}-\mathbf{E}^{21}\mathbf{y}^{11} \qquad (6)$$

As there are both positive and negative terms, $\mathbf{teb}^{1}$ can be greater than, equal to or smaller than zero. Following the convention of merchandise trade, if $\mathbf{teb}^{1}>0$, meaning that emissions embodied in exports are greater than emissions embodied in imports, the Home region is called a net emissions outward flowing region (with the surplus emissions embodied in the trade account).

In a similar vein, Foreign's balance of emissions embodied in trade can be estimated. In our illustrative example, it is not difficult to see that the balance of emissions embodied in trade for the two regions has the zero sum property: i.e., $\mathbf{teb}^{1}+\mathbf{teb}^{2}=0$, or $\mathbf{teb}^{2}=-\mathbf{teb}^{1}$. In fact, the two regions example can be extended to the multi-region (*r* regions) case, where the zero sum property still holds: i.e., $\mathbf{teb}^{1}+\mathbf{teb}^{2}+\cdots+\mathbf{teb}^{r}=0$.

2.3 Balance of CO$_2$ emissions embodied in trade

According to standard trade theory (in particular, the HOV model), a region should export those goods that are relatively intensive in using its relatively abundant factors of production and will import goods that are relatively intensive in using its relatively scarce factors of production. In its extended version, the balance of a factor embodied in trade (positive or negative) should have the same sign as a region's comparative advantage (or disadvantage). Specifically, if a region is relatively abundant in labor, then it is expected that the labor content in exports should be greater than that in imports (Davis & Weinstein, 2001).

For simplicity, CO_2 emissions can be considered as one type of "factor",[1] and according to the HOV model, the net CO_2 emissions embodied in trade should be in accordance with the region's comparative advantage (or disadvantage). Define the gross regional product of region r to be g^r, so its share can be computed as $g^r / \sum_s g^s$. Further define the endowment k in region r to be k^r, so its share is calculated as $k^r / \sum_s k^s$. Similarly, the CO_2 emissions in region r are e^r and its share is given by $e^r / \sum_s e^s$.

Following Davis and Weinstein (2001), it is predicted that: $(e^r / \sum_s e^s - g^r / \sum_s g^s) \times teb^r > 0$. In words, this states that if region r has a higher share of CO_2 emissions than its share of gross regional product, the region can be considered as a region with relatively abundant CO_2 emissions; thus, it is highly likely that the CO_2 emissions embodied in exports are greater than those in imports (i.e., $teb^r > 0$), and *vice versa*.

3. Data issues

---

[1] In fact, CO_2 emissions and other pollutants are by-products associated with production processes, not inputs *per se*. Taking into account the positive correlation between energy inputs and emissions, and for the sake of simplicity, the emissions are considered as a "factor". See Davis and Weinstein (2001) for a detailed discussion of the factor content problem in the HOV framework.

Multi-regional input-output (MRIO) tables have been widely used in measuring CO_2 emissions in trade (see SI, ESR 2009). In general, there are just two types of officially published MRIO tables. One treats a "region" as a country, as in the so-called ICIO (inter-country input-output) tables. WIOD and IDE's Asian IO tables are the most representative cases. The other type of MRIO table treats a "region" as a domestic province (or sub-national area), like China's interregional IO tables (IDE, 2003). If our research interest just focuses on a country-to-country relationship or a domestic region-to-region relationship, the information provided by conventional MRIO tables is satisfactory.

However, in order to investigate how China's regional CO_2 emissions are induced through both domestic and international segments of GVCs, the conventional MRIO tables are no longer enough. We need a new dataset in which China's domestic regions can be fully embedded in an ICIO table. This is for two main reasons. 1) In most ICIO tables, China is treated as a single entry and there is no information about Chinese domestic regions. 2) In most Chinese interregional IO tables, regional exports and imports are treated as exogenous variables, that is, there is no information about who uses Chinese regional exported goods or where Chinese regional imports come from.

In order to overcome the above shortcomings in the existing MRIO tables, Meng et al. (2013b) used a linear programing method to embed the 2007 China interregional IO table into the WIOD table. As shown in the Appendix, this table is a completely closed IO system with four Chinese domestic regions (Northeast, West, Central and Coast) and four foreign country or country groups (the US, Japan, EU and ROW) consistently linked to each other. The most important information used as a bridge to link these two types of MRIO tables is China's regional customs data by country of origin and destination. This data is originally based on the Harmonized System (HS) classification. Using the Broad Economic Categories (BEC) recently proposed by the UNSD, HS-based trade is separated into intermediate, final consumption and capital goods. This helps to improve the precision of estimations. The empirical results of this paper are based on this new dataset.

In addition, CO_2 emissions data at the national level come mainly from the original WIOD database. The Chinese regional and sectoral CO_2 emissions data are calculated from the combustion of fuels and industrial processes using the Intergovernmental Panel on Climate Change reference approach (IPCC 2006). To estimate CO_2 emissions, 18 types of combustion of fuels and industrial processes are used in this study: raw coal, cleaned coal, other washed coal, briquettes, coke, coke oven gas, other gas, other coking products, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquid petroleum gas, refinery gas, other petroleum products, natural gas and other energy. Fuel data for 44 industries and 30 provinces were collected for use in this study from the China Energy Statistical Yearbooks and the China Provincial Statistical Yearbooks for the target year.

4. Main results

We will divide our results into three sub-sections. First, we will present stylized facts regarding the economies explicitly shown in the dataset. These will then be connected to endowments theory, which leads to theoretical predictions about the direction of net CO2 emissions flow. Then, the empirical results based on the newly developed dataset are compared with the results of Meng et al. (2013a) and others. Finally, we compare the empirical results with the sign prediction based on the extended environmental endowments theory.

4.1 Stylized facts

Before analyzing the empirical results, it is helpful to study the diversity of China's regions and other economies.

When dealing with a multiregion, multifactor version of the HOV model, the relative share of a certain factor (in comparison with gross regional product) can be used as an indicator of comparative advantage (see Davis and Weinstein, 2001). In reality, energy inputs, which generate pollutants, are essential components for production. In this sense, pollution associated with production can be considered as an "input" (with negative effects). Thus, it is plausible to derive each region's comparative (dis)advantage by comparing the share of gross regional product and the share of CO_2 emissions in production processes.

Table 1 clearly shows a distinct pattern of comparative advantage between developed economies and others. In fact, the three developed regions of Japan, the USA, and EU27 have shares of CO_2 emissions that are smaller than their shares of gross regional product: for example, 14% CO_2 emissions vs. 29.7% gross regional product for EU27. In contrast, the four regions of China (and ROW) have shares of CO_2 emissions that are greater than their shares of gross regional product: for instance, 9.7% CO_2 emissions vs. 3.5% gross regional product in the China Coast region.

Table 1 Regional characteristics and CO_2 emissions in each region, 2007

	Gross regional product, %	CO_2 emissions (production-based), %	Value added share, %
	$g^r / \sum_s g^s$	$e^r / \sum_s e^s$	
China Northeast	0.6	2.4	37.0
China West	1.2	5.0	40.5
China Central	1.3	4.8	37.1
China Coast	3.5	9.7	29.5
Japan	8.0	4.3	51.1
USA	26.0	18.6	54.8
EU27	29.7	14.0	50.0
ROW	29.8	41.3	50.5
World total	54364.5	25261.7	49.7*

Note: Gross regional product is in 2007 Billion US$; CO_2 emissions in million tons. For value added share, the world total gives an average of the whole world (i.e., the sum of world GDP over the sum of world total inputs for each region).

This novel dataset also enables us to calculate each region's value added share. Surprisingly, regions other than China have value added shares of over 50%; whereas the four regions of China have no more than 41% (falling even as low as 29.5% for China Coast). One reason may be that, for developed economies, the service industry that usually has a high value added share forms a relatively larger share of the economy. More importantly, this observation has implications for development strategy, for instance, regarding the emphasis on service industry development in China's "Twelfth Five-year Plan", which takes into account that service industries have the features of low-carbon and high value-added.

4.2 Empirical results

The previous section gives a descriptive analysis of the nature of each region's comparative advantage in terms of CO_2 emissions. In this section we will focus on the estimation of flows of CO_2 emissions among regions (the four regions of China and the other economies).

It is not difficult to see that from a row-wise reading of Table 2 we can get production-based accounting results (i.e., equation (3a)); while for a column-wise reading, the consumption-based accounting principle is employed (i.e., equation (3b)).[1] Several observations can be made from Table 2.

First, values on the diagonal are the largest for each row, meaning that the biggest share of CO_2 emissions generated from production can be accrued to a region's own final demand. For example, the value 4238.3mt (row 7 and column 7) gives the CO_2 emissions generated in the USA due to final demand in the USA. This result is perfectly intuitive.

Second, along each row, we can calculate each region's own share of responsibility for total emissions from production. Strikingly, China's four regions have shares ranging from 41% (North) to 47% (China Coast)[2], substantially lower than other regions in the world (e.g., the USA has a share of no less than 90%), which means that at least half of emissions are generated due to final demand from other regions. This is a typical result of production sharing and is particularly pervasive in China's regions.

---

[1] Note that, due to space constraints, only aggregate results are reported in this paper. Industry level results are available upon request.

[2] It may be argued that, smaller economies tend to be more open. So we calculated the share for China as a whole and it turns out that the share increases to some extent (to roughly 69%). Still this value is far lower than that of developed economies, such as Japan (81%), EU27 (84%), and even lower than for ROW (78%). It should be stressed that, processing trade is not explicitly dealt with in this dataset, which may overstate the extent of foreign dependence (see Dietzenbacher et al., 2012, for a single country study).

Table 2 Production sharing and CO_2 emissions due to final uses (million tons), 2007

	China Northeast	China West	China Central	China Coast	Japan	USA	EU27	ROW
China Northeast	247.5	39.5	55.0	115.6	16.1	31.6	32.5	67.7
China West	41.6	520.4	154.6	255.7	22.1	64.3	62.7	131.6
China Central	19.8	70.3	542.1	253.5	25.7	77.9	76.8	149.4
China Coast	36.0	128.7	171.6	1161.3	77.0	247.1	215.5	410.8
Japan	1.4	2.2	2.9	19.7	877.3	40.8	33.6	102.3
USA	1.4	2.9	3.0	19.9	26.2	4238.3	113.6	288.2
EU27	3.1	3.7	4.1	26.2	23.9	135.2	2963.3	376.0
ROW	15.1	29.0	34.6	186.9	224.9	826.5	935.5	8177.8

Source: Authors’ calculation based on the novel dataset.

Note: Values in each cell give the CO_2 emissions generated in the regions in the column due to final consumption in regions in the row, and values in diagonal are emissions due to a region’s own final demand. For example, the value 115.6 (column five and row two) means to fulfill the final demand in the China Coast region, 115.6mt CO_2 were generated in China Northeast.

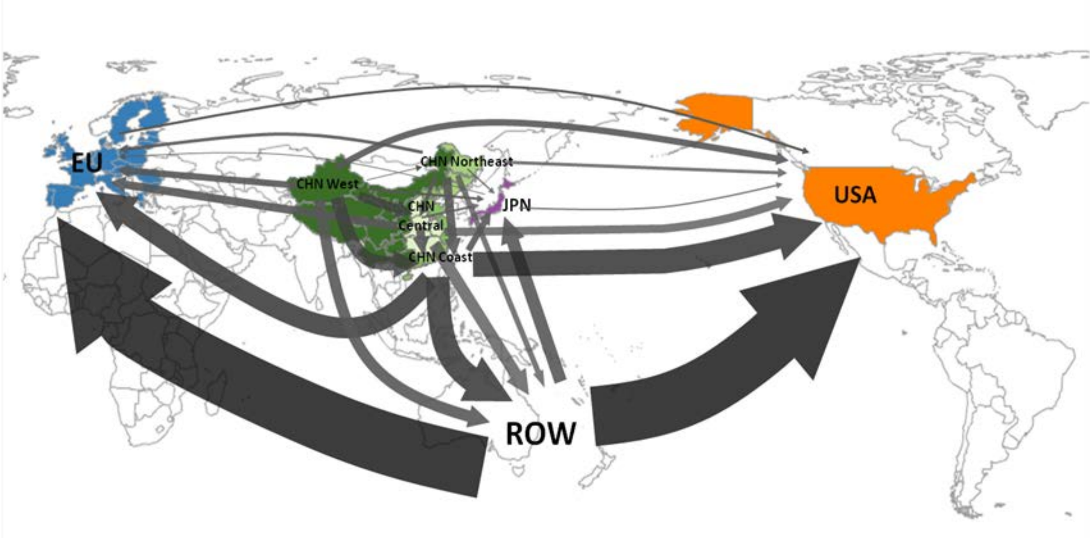
Third, when comparing our results with those of Meng et al. (2013a), it is clear that we add new information about regional responsibility for CO_2 emissions. This is valuable in two respects: on the one hand, it is possible to position regions in a global supply chain (the CO_2 emissions chain); on the other hand, the carbon leakage issue can be explicitly tackled.

In terms of industries, two industries top the rank of production-based accounting

CO_2 emissions for all four regions of China, namely the *material and process industry* and *construction* (see Appendix 1 for sector classifications). This observation comes as no surprise if we realize that China's production mix (or GDP composition) is biased towards secondary industry. At the same time, it can be seen that consumption-based CO_2 emissions are mainly due to gross capital formation.

For comparison, the production-based CO_2 emissions in the USA, whose pattern of emissions is different from the rest, came from construction and services. One of the primary reasons would be that the USA has outsourced a substantial amount of production activity. In sharp contrast to China, consumption-based CO_2 emissions in Japan, the USA, EU27 and ROW were all dominated by private consumption. And it is found that, take the USA as an example, her private consumption caused CO_2 emissions in China amounted to 238.6mt (the region with the biggest share of the responsibility was China Coast which contributed 59% of the total).

Figure 1 CO_2 emissions embodied in net exports with China split into regions, 2007



Source: Authors' compilation based on the novel dataset.

Interestingly, it can be seen from Figure 1[1] that inland regions (say, China West and China Central) also have massive CO_2 emissions embodied in net exports to EU27, the USA and ROW. In fact, these inland regions do not export a lot of goods and service to foreign countries directly, particularly when compared with coastal regions. However, indirectly, they have been deeply involved in GVCs. One of the most plausible interpretations would be because they are located relatively upstream along the production chain and thus provide huge amounts of intermediate goods and natural resources (normally with high-carbon intensity) to downstream and exporting regions (i.e., China Coast). It can be seen that these intermediate goods are embodied in final goods assembled and produced in China Coast and ultimately exported to EU27, the USA and ROW. This observation helps to explain why inland regions also export (albeit in an indirect manner) large amounts to foreign economies. In other words, inland regions within a country can also join GVCs via an indirect route.

At the same time, more emissions may be generated to fulfill foreign demand since environmental regulation in China's inland regions tends to be weaker.[2] In this regard, common but differentiated responsibilities should also be proposed at a regional level within one country, e.g. China. Specifically, inland regions should implement the same stringent environment regulations that are in place elsewhere and, to remedy the downsides of relatively poor technology, a certain amount of technology transfer or

---

[1] We are indebted to Miao Yu from Tsinghua University for providing assistance in preparing the Figure.

[2] Fortunately, the USA and China, two giant emitters in the world, jointly announced respective targets for CO_2 emissions reduction during the APEC Summit held in Beijing, 2014. China aims to reach the peak of absolute CO_2 emissions in 2030 at the latest, while the USA promises to reduce CO_2 emissions intensity by about 25%-28% in 2025 relative to the 2005 level. To achieve these ambitious goals, empirical studies and careful policy recommendations are needed, for example, identifying the main sources for CO_2 emissions will help to fix policy priorities.

even monetary aid from coastal regions needs to be in place (similar to the so-called Clean Development Mechanism, or CDM, in a global context). Such an arrangement is relatively easy in China; the main advantage is that there is central government which can design policy to motivate regional actions. In fact, some movement, albeit partial, in this direction has been observed (e.g., there are seven pilot cities or provinces in the Emissions Trading System, or ETS). To achieve a nation-wide goal of CO_2 emissions reduction, interregional carbon leakage needs to be taken fully into consideration.

It can also be seen from Figure 1 that China's interregional carbon leakage is remarkable: in particular, inland regions (e.g., Northwest) export substantial amounts of CO_2 emissions to coastal regions. If the ETS only covers intra-region emissions trading and production activities within a region, then only part of the story is revealed. Ideally, a nationwide ETS market should be formed, and by designing a national goal for CO_2 emissions reduction, a top-down approach can be adopted to allocate the national reduction at the regional level. Then, through the national CDM, inland regions will also benefit from stringent environmental regulations. This is also relevant for global climate change policy, although perhaps to lesser extent—since there is no "central government" above all sovereign economies, a binding agreement is not easy to obtain. Luckily, by employing the "transnational and interregional" framework, our novel data can provide empirical evidence to support such efforts.

4.3 Balance of CO_2 emissions embodied in trade

The basic idea of the sign test for balance of CO_2 emissions embodied in trade is straightforward: it states that the sign of one economy's percentage share of a factor *minus* its percentage share of world GDP equals the sign of that economy's factor content of net exports.

Table 3 Comparative advantage, CO_2 emissions embodied in trade and empirical test, 2007

	Relative CO_2 emissions abundance, %	CO_2 emissions embodied in exports	CO_2 emissions embodied in imports	Empirical test
China Northeast	1.8	358.1	118.5	+
China West	3.8	732.6	276.3	+
China Central	3.5	673.4	425.7	+
China Coast	6.2	1286.7	877.5	+
Japan	-3.7	202.9	416.0	+
USA	-7.4	455.3	1423.2	+
EU27	-15.7	572.1	1470.3	+
ROW	11.5	2252.5	1526.1	+

Note: CO_2 emissions embodied in trade are in million tons.

Table 3 gives the results of this sign test. The second column is obtained by taking the difference of column three (share of CO_2 emissions) and column two (share of world GDP) in Table 1, which can be used as a proxy for comparative advantage. By using equations (3a) and (3b), the amounts of CO_2 embodied in exports and in imports are estimated (columns three and four). The last column gives the results of the sign test, i.e., the sign of each region's CO_2 content of net exports (column three *minus* column four) times the sign of that region's relative CO_2 abundance (column two).

It seems that the environmental version of the HOV model performs fairly well, which is confirmed by the data (see the positive signs in the last column).[1] This relates to recent discussion regarding the so-called "Green Leontief Paradox" (see Dietzenbacher and Mukhopadhyay, 2007), for which we do not find any support. In other words, in general, the validity of the extended environmental HOV model is supported by our study. This is an important message, meaning that we can explain and even predict the flows of CO_2 emissions in such a theoretical framework. We suspect that this result holds not only for CO_2 emissions but also for other pollutants.

Furthermore, our results are relevant to the debate about the "pollution haven hypothesis" and the "factor-endowment hypothesis" (see Temurshoev, 2006; Copeland and Taylor, 2004). Evidently, the factor (as well as pollutant) content of net exports depends largely on the economy's endowments (relative abundance or scarcity). In this regard, structural changes or upgrading production technology within each region are the best choice for climate change mitigation.

5. Conclusion and discussion

Production sharing is a major characteristic of today's economy. It is thus relevant to consider CO_2 emissions embodied in trade in the context of global value chains (GVCs) even if the focus is on domestic regions. This paper considers a novel dataset describing eight regions and eight sectors for year 2007. The dataset covers four regions of China, together with Japan, the USA, the EU27 and ROW. A demand spillover perspective is adopted to allocate emissions responsibilities between producers and consumers so that CO_2 emissions embodied in trade can be estimated. The empirical

---

[1] The results shown here include interregional flows within China. We have conducted similar analysis excluding interregional flows within China (which can be readily checked by simple calculations using Table 2). The conclusions still hold.

results were interpreted using an extended environmental HOV model, and an empirical test was performed. Strikingly, the directions of CO_2 emissions embodied in net exports were entirely predicted by our theoretical framework.

In particular, the four regions of China are upstream regions in the GVCs and are endowed with energy inputs (thus CO_2 emissions); therefore, their exports were CO_2 emissions intensive. This observation holds also for China as a whole. Within China, it is also clear that, China Coast was relatively downstream, in a position of importing CO_2 emissions from the rest of China. These findings are relevant to the current debate on the "pollution haven hypothesis" and the "factor endowment hypothesis". It seems factor endowments are the ultimate determinants of the pattern of factor content (either CO_2 emissions or other factors) in net exports.

In terms of policy discussions, input structure and production technology play crucial roles in determining the pattern of trade and, given a technology, factor endowments are fundamental determinants of the production pattern. This is old wisdom that has been around since the beginning of the Heckscher-Ohlin theorem. What is new here is that our paper confirms such predictions in a broader sense and provides a micro interpretation of empirical findings. In this regard, the policy recommendation would be to target micro mechanisms that determine the comparative advantage. For instance, a tax reform for coal from the amount levied to an *ad valorem* fashion will change the relative price of energy inputs and thus have an impact on the input choice of producers, which will eventually change the emissions content in production.

Equally important is that a nationwide ETS is urgently called for, given the fact that interregional carbon leakage is severe. To remedy the downside of poor technology found in inland regions, technology transfer or monetary redistribution should be implemented by central government. This would help to achieve the CO_2 emissions peak as early as possible and it is believed that unilateral movement towards a low-carbon economy is also beneficial to the global environment.

References

[1]. Bems R., Johnson R. and Yi K. (2010) Demand spillovers and the collapse of trade in the global recession. IMF Economic Review 58, 295-326.

[2]. B.R. Copeland, M.S. Taylor, Trade, growth, and the environment, Journal of Economic Literature 42 (2004) 7–71.

[3]. E. Dietzenbacher, K. Mukhopadhyay, An empirical examination of the pollution haven hypothesis for India: towards a green Leontief paradox? Environmental and Resource Economics 36 (2007) 427–449.

[4]. Erik Dietzenbacher, Jiansuo Pei and Cuihong Yang (2012). Trade, Production Fragmentation, and China's Carbon Dioxide Emissions, Journal of Environmental Economics and Management, 64: 88-101.

[5]. Gene Grossman and Alan Krueger (1993). Environmental impacts of a North American Free Trade Agreement, in The Mexico-US Free Trade Agreement, ed. Peter M. Garber, 13-56. Cambridge, MA: MIT Press.

[6]. IDE (2003). Multi-regional Input-Output Model for China 2000.

[7]. Kuishuang Feng, Steven J. Davis, Laixiang Sun, Xin Li, Dabo Guan, Weidong Liu, Zhu Liu and Klaus Hubacek (2013). Outsourcing CO2 within China. PNAS, 110(28): 11654-11659.

[8]. Arik Levinson (2009). Technology, international trade, and pollution from US manufacturing. American Economic Review, 99(5): 2177-2192.

[9]. Liu, Z., Y. Geng, S. Lindner, and D. Guan (2012). Uncovering China's greenhouse gas emission from regional and sectoral perspectives, Energy, 49(1): 1059-1068.

[10]. Meng, B., J.J. Xue, K.S. Feng, D.B. Guan and X. Fu (2013a). China's interregional spillover of carbon emissions and domestic supply chains. Energy Policy, 61: 1305-1321.

[11]. Meng, B., Wang, Z., and R. Koopman (2013b). How are Global Value Chains Fragmented and Extended in China's Domestic Production Networks?, IDE Discussion Papers, No.424.

[12]. Robert C. Johnson and Guillermo Noguera (2012). Accounting for intermediates: Production sharing and trade in value added, Journal of International Economics, 86(2): 224-236.

[13]. Peters, Glen (2008). From Production-Based to Consumption-Based National Emission Inventories. Ecological Economics, 65(1): 13-23.

[14]. Peters, Glen and Edgar G. Hertwich (2008). CO2 embodied in international trade with implications for global climate policy. Environmental Science and Technology, 42 (5): 1401-07.

[15]. Peters, G.P. J.C. Minx, C.L. Weber and O. Edenhofer (2011), Growth in emission transfers via international trade from 1990 to 2008, PNAS, 108(21): 8903-08.

[16]. Qi, Y., H., Li and T. Wu (2013). Interpreting China's carbon flows, PNAS, 110(28): 11221-22.

[17]. Special Issue: Carbon Footprint and Input–Output Analysis (2009), Economic Systems Research, 21(3).

[18]. U. Temurshoev. (2006), Pollution haven hypothesis or factor endowment hypothesis: theory and empirical examination for the US and China, CERGE-EI Working Paper 292.

[19]. M.P. Timmer, A.A. Erumban, B. Los, R. Stehrer and G.J. de Vries (2014), Slicing Up Global Value Chains, Journal of Economic Perspectives, 28(2), 99-118.

[20]. M.P. Timmer, B. Los, R. Stehrer and G.J. de Vries (2013), Fragmentation, Incomes and Jobs: An Analysis of European Competitiveness, Economic Policy, 28, 613-661.

[21]. C.L. Weber, G.P. Peters, D. Guan, K. Hubacek (2008), The contribution of Chinese exports to climate change, Energy Policy, 36: 3572–77.

i. Appendix 1 Sector classification

		Sector classification used in the paper							
		1	2	3	4	5	6	7	8
Code	**Sectors in China's MRIO table**	Agriculture	Mining and quarrying	Life-related industry	Process industry	Assembly Industry	Electricity, Gas and Water Supply	Construction	Other services
1	Agriculture	✓							
2	Mining and quarrying		✓						
3	Food products and tobacco			✓					
4	Textile and garment			✓					
5	Wooden products and furniture				✓				
6	Pulp, paper and printing				✓				
7	Chemical				✓				
8	Non-metallic mineral products				✓				
9	Metal products				✓				
10	General mechinary					✓			
11	Transport equipment					✓			
12	Electric apparatus, electronic and telecommunications equipment					✓			
13	Other manufacturing products			✓					
14	Electricity, gas, and water supply						✓		
15	Construction							✓	
16	Trade and transportation								✓
17	Other services								✓
Code	**Sectors in WIOT**								
1	Agriculture, Hunting, Forestry and Fishing	✓							
2	Mining and Quarrying		✓						
3	Food, Beverages and Tobacco			✓					
4	Textiles and Textile Products			✓					
5	Leather, Leather and Footwear			✓					
6	Wood and Products of Wood and Cork				✓				
7	Pulp, Paper, Paper , Printing and Publishing				✓				
8	Coke, Refined Petroleum and Nuclear Fuel				✓				
9	Chemicals and Chemical Products				✓				
10	Rubber and Plastics				✓				
11	Other Non-Metallic Mineral				✓				
12	Basic Metals and Fabricated Metal				✓				
13	Machinery, Nec					✓			
14	Electrical and Optical Equipment					✓			
15	Transport Equipment					✓			
16	Manufacturing, Nec; Recycling					✓			
17	Electricity, Gas and Water Supply						✓		
18	Construction							✓	
19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel								✓
20	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles								✓
21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods								✓
22	Hotels and Restaurants								✓
23	Inland Transport								✓
24	Water Transport								✓
25	Air Transport								✓
26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies								✓
27	Post and Telecommunications								✓
28	Financial Intermediation								✓
29	Real Estate Activities								✓
30	Renting of M&Eq and Other Business Activities								✓
31	Public Admin and Defence; Compulsory Social Security								✓
32	Education								✓
33	Health and Social Work								✓
34	Other Community, Social and Personal Services								✓
35	Private Households with Employed Persons								✓

Appendix 2 Country and Chinese domestic region classification

Countries in WIOT	Countries or country-group used in the paper				
	CHN	JPN	USA	EU	RoW
AUS					✓
AUT				✓	
BEL				✓	
BGR				✓	
BRA					✓
CAN					✓
CHN	✓				
CYP				✓	
CZE				✓	
DEU				✓	
DNK				✓	
ESP				✓	
EST				✓	
FIN				✓	
FRA				✓	
GBR				✓	
GRC				✓	
HUN				✓	
IDN					✓
IND					✓
IRL				✓	
ITA				✓	
JPN		✓			
KOR					✓
LTU				✓	
LUX				✓	
LVA				✓	
MEX					✓
MLT				✓	
NLD				✓	
POL				✓	
PRT				✓	
ROM				✓	
RUS					✓
SVK				✓	
SVN				✓	
SWE				✓	
TUR					✓
TWN					✓
USA			✓		
RoW					✓

Provinces in China	Region classification used in the paper			
	NorthEast	West	Center	Coast
Beijing				✓
Tianjin				✓
Hebei				✓
Shanxi			✓	
Neimenggu		✓		
Liaoning	✓			
Jilin	✓			
Heilongjiang	✓			
Shanghai				✓
Jiangsu				✓
Zhejiang				✓
Anhui			✓	
Fujian				✓
Jiangxi			✓	
Shandong				✓
Henan			✓	
Hubei			✓	
Hunan			✓	
Guangdong				✓
Guangxi		✓		
Hainan				✓
Chongqing		✓		
Sichuan		✓		
Guizhou		✓		
Yunnan		✓		
Tibet		✓		
Shaanxi		✓		
Gansu		✓		
Qinghai		✓		
Ninxia		✓		
Xinjiang		✓		

Chapter 4

The Impact of Firm Heterogeneity in Measuring China's Carbon Footprint

Yu LIU[1], Bo MENG[2], Yuning GAO[3], Xiaofeng LI[4]

Abstract: Input-Output (IO) tables provide a complete record of commodity & service flows between producers and consumers in the economy for a given year. This record can help us easily identify how many different types of energy goods are used as intermediate inputs for producing a specific product. Given this advantage, IO tables have been widely used in measuring carbon dioxide emissions at both national and industrial levels. In a traditional IO table, firms are allocated in the same sector if they produce goods which have the same name. However, the problem is that there may be a large variation in the production function and the pattern of energy use across firms who have different ownership, size, trade mode, even if they are allocated in the same sector. This attracts our attention: if the absence of firm heterogeneity information in traditional IO tables may cause a potential bias in measuring industrial CO2 emissions and carbon footprint? Using the firm-level Chinese national IO table for 2007 (a by-product from Ma et al. 2013), we re-measured the industrial CO2 emissions, carbon footprint and carbon intensity of embodied CO2 emissions for China and compared to the results measured by the conventional IO table. The measuring results show that in 2007, 93% of emissions come from Chinese owned enterprises with high carbon emission intensity, while only a small part of emissions come from other types of firms, with relatively low intensity. Carbon emissions and intensity for firms who engage the non-processing trade are much greater than those of firms involved in the processing trade. Comparative analysis results show that ignoring firm heterogeneity will make the embodied carbon for export overvalued by 20%, and that of domestic final demand underestimated by about 7%. Such kind of estimation bias is more considerable at the sector level. For example, the embodied carbon emission of domestic final demand in communication equipment sector is 70% higher than the ordinary calculated results. In addition, after introducing a new index - embodied carbon emission intensity, the results indicate that foreign-invested enterprises produce a few emissions, but will greatly induce relative more carbon emissions of upstream Chinese owned enterprises who are involved in the non-processing trade. Although considering firm heterogeneity will not change the measuring results for China's national carbon emissions, it will significantly reduce the potential bias when measuring industrial carbon emissions and carbon footprint, at the same time, help us better understand the internal relationship between the division of production process and carbon emissions among different types of enterprises in China's domestic production networks.

Keyword: Firm heterogeneity, CO2 emissions, processing trade, carbon intensity

1: Yu LIU, Associate professor, Institute of Policy and Management, Chinese Academy of Sciences, China

2: Bo MENG, Research Fellow, IDE-JETRO, Japan

3: Yuning GAO, Assistant Professor, School of Public Policy and Management, Tsinghua University, China

4: Xiaofeng LI, Master's Student, Beihang University

1. Introduction

Nowadays information related to carbon dioxide emissions (hereinafter referred to as carbon emissions) is mainly based on the statistics and measurement at the national and industry level. The most commonly used information at the national level is data from IEA's CO_2 Emissions from Fuel Combustion (2014). While at the industry level is WIOD (World Input - Output Database, see Marcel p. Timmer, 2012), etc. Information above plays a huge role in picturing carbon emission tendency, participating in the international negotiations and making the domestic industry emission reduction policy. However, due to global economic integration, carbon emissions information at the national and industry level cannot meet our policy demands for responding the international challenges. In China's industries, is Chinese owned firm [1]or foreign-owned firm in China[2] the heaviest carbon dioxide emitter? Which one have higher energy consumption and how much higher? How much emission will state-owned firms produce when cooperate with foreign-owned firms? Will the same carbon tax produce different influences on emissions of state-owned firm and foreign-owned firm, and then on employment? How big those influences are? Is the impact brought by energy tax on the large firms bigger than small and medium-sized firms? How much bigger? If foreign countries charge carbon tariffs on the products or services from China (such as air transport), what influence will different firms and their downstream firms receive? Before answering the above problems, we must have the information on energy consumption and carbon emission which can reflect the firm heterogeneity (it mainly

---

[1] According to international practices, Chinese-owned firms refer to the firm with Chinese citizen or legal person investing or holding more than 50%.

[2] Foreign-owned firms refer to the firm with foreign citizen or legal person investing or holding more than 50%.

includes the firm ownership, the way of firms conducting trade activities, etc.). As one sentence “You can’t manage what you can’t measure” commonly used in management science, measuring carbon emissions of firms of different ownerships are the first step and the prerequisite for us to provide policy suggestions.

With China as an example, this paper is to use the firm heterogeneity information to measure carbon emission of different industries and embodied carbon also known as the carbon footprint. It then makes a comparison with the results of traditional measurement to assess the importance and indispensability of firm heterogeneity.

For China, firm heterogeneity is very obvious in the field of economy. At present, firms in China can be roughly divided into the Chinese-owned firm and foreign-owned firm according to ownership, non-processing trade and processing trade [1]according to the mode of trade. There is a high proportion of foreign-owned firms in many industries, foreign direct investment (FDI), and many processing trades. As shown in the figure below, Chinese-owned firms engaging in the non-processing trade account for the vast majority of China’s GDP, and foreign-owned firms engaging in the non-processing trade account for about 10% of GDP. The sum of the two is the proportion of firms engaging in the non-processing trade, accounting for around 97% of GDP. On the other hand, Chinese-owned firms and foreign-owned firms engaging in the processing trade account for 0.5% and 2.3% of GDP. In total, processing trade accounts for about 3% of GDP.

---

[1] According to the regulation in *PRC Customs Supervision and Administration of Processing Trade Goods Procedures* (Order No. 219 of the General Administration of Customs), processing trade refers to the business activities that the firm imports all or part of raw and auxiliary materials, spare parts, components and packing materials, conduct the processing or assembling, and finally reexports the finished products, including processing of imported materials and processing of supplied materials. Non-processing trade refers to the trade type other than the processing trade.

Chinese-owned firms account for 87.3% of GDP, and foreign-owned firms account for 12.7% of GDP.

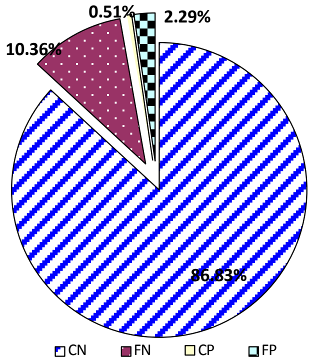


Figure 1 GDP proportion of firms with different ownerships (2007)

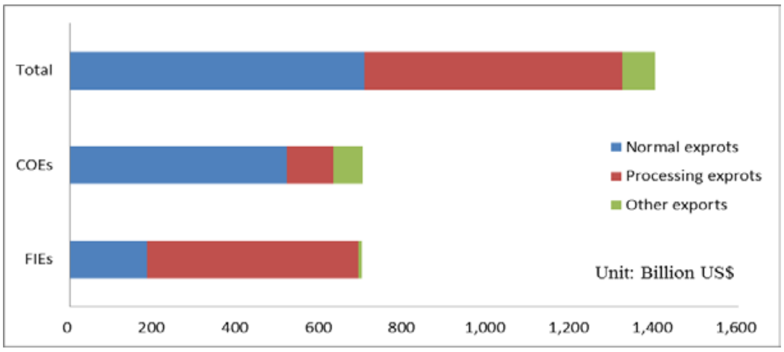


Figure 2 Exports proportion of firms with different ownerships (2011)

From the perspective of export (figure 2), nearly 44% of total exports of Chinese goods in 2011 is from processing trade, and 82% of the processing trade is from foreign-owned firms. From the perspective of firm ownership, processing trade accounts for about 72% of total exports of foreign-owned firms, with exports of 506 billion dollars, but for Chinese-owned firms, the proportion is only 16%, with amount of about 111 billion dollars. These data fully show that China’s firm heterogeneity so obvious that can’t be ignored in studying Chinese economy.

However, so far, there is still very little literature on using firm heterogeneity to measure carbon emission. There are two ways of measuring the traditional carbon emissions of different industries. One is a bottom-up way. It is using detailed energy usage information to measure the carbon emissions, and then obtains the measurement results of different industries according to the corresponding relation between the firm and industry sector. The other way is to make full use of the information in the input-output table and energy balance table to directly measure carbon emissions of different industries. The advantages of the former are large amount of information, including the firm heterogeneity information, simple and understandable measurement methods. The disadvantage of it is that it requires a great deal of manpower, material resources and time to obtain such comprehensive enterprise survey information. In contrast, the latter method uses the market supply-demand relationship among various economic subjects in the input-output table, together with some assumed conditions, is much more economic and efficient. So this method is widely used (see Lenzen, 1998, Schaeffer, 1996, Machado et al., 2001, etc.). However, since the input-output table and energy balance sheet published exclude the firm heterogeneity information, carbon emissions of firms with different ownerships in the same industry cannot be reflected based on their measurement. This paper uses input-output table with the firm heterogeneity information and the energy balance sheet to conduct the measurement of carbon emissions of different industries of China. Results show that firm heterogeneity is of great significance for more comprehensive understanding of carbon emissions and embodied carbon structure of different industries and improving the measurement validity. Carbon dioxide emissions of firms with different ownerships vary drastically. For direct carbon emissions, Chinese-owned firms emit more than foreign-owned firms and the non-processing trade firms emit more than processing trade firms. For firms with different ownerships, carbon emissions of various industries are also different. Major carbon emitter of Chinese-owned firms mainly includes electricity and heat production and supply industry, metal smelting and rolling processing industry, chemical industry, non-metallic mineral product industry as well as transportation and post and warehousing industry. Major carbon emitter of foreign-owned firms mainly includes chemical industry, metal smelting and rolling processing industry, non-metallic mineral product industry, etc. In addition to direct carbon emissions, the firm heterogeneity tends to lead to different results from traditional method in the measurement of carbon emission intensity and embodied carbon emissions. For example, carbon emission intensity of Chinese-owned firms is generally higher than that of foreign-owned firms, and carbon emission intensity of non-processing trade is generally higher than that of processing trade. When calculating the embodied carbon for export and final use, if the firm heterogeneity is ignored, it will cause Leontief Inverse[1] difference, thus resulting to obvious calculation errors. To sum up, research on firm heterogeneity is of great significance for the measurement of carbon emissions.

This paper is divided into five parts. The first part above introduces our purpose of research, background and related literature. The second part mainly explains the data selection and measurement method. The third part uses the input-output table with the firm heterogeneity information to make the measurement of direct carbon emissions and carbon emission intensity in industrial sector. It also makes comparative analysis with the traditional results. The fourth part makes the measurement of embodied carbon for

---

[1] Leontief inverse matrix is the result of direct consumption coefficient matrix inversion in the input-output model. It represents the gross output caused directly and indirectly by unit final demand through the inter-industry multiplier effect. Its calculation formula is $L = (I - A^T)^{-1}$, where, A is direct consumption coefficient matrix.

export and final domestic demand to show the error may caused by ignoring firm heterogeneity. At the same time, we introduce the new concept of embodied carbon emission intensity to interpret the relationship between the extent of firms with different ownerships participating in the supply chain and their carbon emissions. The fifth part is the conclusion and some policy suggestions.

2. Summary of Data and Carbon Emission Measurement Methods

Data selected for measuring direct carbon emissions and embodied carbon emissions of different industries and firms with different ownerships mainly includes 2007 energy balance sheet of China, 2007 national input-output table (short for the national table, and now it is also the latest survey-based input-output table issued by the authority), 2007 national input-output table (short for firm table) of firms with different ownerships, as well as some commonly-used international energy emission factor data. Specific data sources are as shown in table 1.

Table 1 Data sources

Data used	**Data usage**	**Data sources**
Energy balance sheet of China in 2007	Calculation of energy usage amount of different types of energy	*China Energy Statistical Yearbook-2008*
2007 national input-output table of 42 sectors of firms with different ownerships (short for the firm IO table)	Access to energy supply and demand information of different industries	Ma, et al. (2013).
2007 input-output table of China's 42 sectors	Access to energy supply and demand information of different industries	*2007 China's Input-Output Table*
Carbon dioxide emissions of various energy sources under the unit calorific value (short for the national table)	Calculation of CO_2 emission factor of energy sources	*2006 IPCC National Greenhouse Gas Inventory Guide*
Average lower heating value of various energy sources	Calculation of CO_2 emission factor of energy sources	*China Energy Statistical Yearbook-2008*
Reference coefficient of standard coal of various energy sources	Calculation of energy conversion rate	*China Energy Statistical Yearbook-2008*

Table 2 National Input-Output table with firm heterogeneity information

		Intermediate Transaction				Final Demand	Export	Total output
		Chinese owned firm		Foreign-owned firm				
		Non-processing	Processing	Non-processing	Processing			
Chinese owned firm	Non-processing	X_{ij}^{11}	X_{ij}^{12}	X_{ij}^{13}	X_{ij}^{14}	F_1	EX_1	Y_1
	Processing	0	0	0	0	0	EX_2	Y_2
Foreign-owned firm	Non-processing	X_{ij}^{31}	X_{ij}^{32}	X_{ij}^{33}	X_{ij}^{34}	F_3	EX_3	Y_3
	Processing	0	0	0	0	0	EX_4	Y_4
Import		X_{ij}^{51}	X_{ij}^{52}	X_{ij}^{53}	X_{ij}^{54}	F_5	0	0
Value Added		V_1	V_2	V_3	V_4			
Total Input		Y_1	Y_2	Y_3	Y_4			

Among above data, input-output table of firms with different ownership is the important information source for us to re-estimate carbon emissions. This paper applies the input-output table with firms ownership compiled by Ma et al. (2013) (detailed format is as shown in table 2) to divide all industries into energy industry and non-energy industry and combined the energy industries according to type of energy. The firm heterogeneity is as follows: intermediate used includes two types of firms, Chinese owned firm and foreign-owned firm, and each type respectively is divided into firm engaging in the non-processing trade goods production and processing trade goods production

In the calculation of carbon emissions, emissions of firms with different ownerships are calculated according to their energy use situation. Since the sum of all industrial sectors is in accordance with national table, definition and calculation results of the direct carbon dioxide emissions of different industries from 2007 national table and firm table are consistent.The concrete measurement method of carbon emissions of different industries is showed as followed. Carbon dioxide emissions of different industries are mainly calculated by total energy consumption of different industries multiplying by carbon dioxide emissions of various energy sources under per unit investment. Total energy consumption of different industries can be obtained from input-output table. Therefore, this paper first measures the carbon dioxide emissions of various energy sources under per unit investment. There are 4 types of energy industries in the input-output table: coal mining and washing industry, petroleum and natural gas extraction industry, oil processing coking and nuclear fuel processing industry, and gas production and supply industry. This paper focuses on calculating the carbon dioxide emissions of these four types of energy industry under per unit investment. The calculation steps according to the national table are as follows:

(1) Carbon dioxide emission factor with unit heat quantity in *2006 IPCC National Greenhouse Gas Inventory Guide* is multiplied by the average lower heating value in *2007 Energy Statistical Yearbook* to get the emission factor of carbon dioxide from various energy sources per unit mass.

(2) These emission factors are multiplied by the respective energy consumption (*2007 National Energy Balance Sheet*[1]) to get the total carbon dioxide emissions from various energy sources in 2007, as shown in formula (1).

$$E = \sum_k E^k = \sum_k C^k \times w^k \qquad (1)$$

Where, E^k is carbon dioxide emissions from energy k burning, C^k is burning capacity of energy k, w^k is carbon dioxide emission factor of energy k burning.

(3) Match the types of energy sources in the energy balance sheet with the energy industry in the input-output table to measure total carbon emissions of four types of energy industry. Corresponding relationship between the two is: coal mining and washing industry includes raw coal, cleaned coal and other washed coal; petroleum and natural gas extraction industry includes raw petroleum and natural gas; oil processing, coking and nuclear fuel processing industry includes gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas, refinery dry gas and other petroleum products; and gas production and supply industry includes coke oven gas and other gas.

(4) Calculate total amount of money demanded of these four types of energy

---

[1] Energy consumption of energy is get by the final consumption of various energy sources in the energy balance sheet minus the part used for industrial raw materials, and plus the consumption of thermal power and heating.

source according to the input-output table[1]. Total carbon emission of four types of energy sources obtained from (3) is divided by the respective total amount of money of energy source to get the carbon dioxide emissions of four types of energy sources under unit amount of money, as shown in formula (2).

$$e^k = E^k \big/ D^k \tag{2}$$

Where, e^k is carbon dioxide emission factor of energy k based on the value quantity unit, E^k is the total amount of money of energy k used for burning.

(5) Input amount of four types of energy sources of different industries in the input-output table is multiplied by the corresponding per unit amount of money of carbon emissions respectively to get energy carbon emissions of different industries consuming different energy sources, and then these emissions add up to get the total carbon emissions of the corresponding industry, as shown in formula (3).

$$E_j = \sum_k E_j^k = \sum_k C_j^k \times e^k \tag{3}$$

Where, E_j is carbon dioxide emissions of the industry j, E_j^k is carbon dioxide emissions brought by energy k burning in the industry j, C_j^k is energy k burning in the industry j.

Since the energy industry in the firm table is divided into four ownerships of firm, but there is no distinction of firm ownerships in energy supply and use in the energy balance sheet, so we assume that the per unit amount of money of carbon emissions have no connections with the firm ownerships. That is to say, as long as the amount of

---

[1] Total money of energy use is the total domestic energy for burning. Including the intermediate part used of various energy sources (removing the part of not burning but conversion) in the input-output table and energy consumption spending by residents for final use.

money is same, firms produce same amount of carbon emmition.

3. Analysis on Direct Carbon Emission Based on Firm Heterogeneity

3.1 Carbon emission structure of firms with different ownerships

According to the measurement results from firm table, China's total carbon dioxide emissions in 2007 reach 6.070109 billion tons. This result is closed to 5.962552 billion tons of China's emissions in 2007 published by WIOD. Total carbon dioxide emissions of Chinese-owned firms engaging in the non-processing trade goods production, Chinese-owned firms engaging in the processing trade goods production, foreign-owned firms engaging in the non-processing trade goods production, and foreign-owned firms engaging in the processing trade goods production in the process of production is 5.625299 billion tons, 14.333 million tons, 413.983 million tons and 16.493 million tons respectively. According to firms with different ownerships, proportion of Chinese-owned firms engaging in the non-processing trade goods production is 92.7%, far more than that of those engaging in the processing trade goods production (0.2%). Proportion of foreign-owned firms engaging in the non-processing trade goods production is 6.8%, also more than that of those engaging in the processing trade goods production (0.3%). To sum up, from the perspective of the producers, China's largest carbon dioxide emitter in 2007 is Chinese-owned firms engaging in the non-processing trade goods production, foreign-owned firms engaging in the non-processing trade goods production have few contributions, and other new firms have less carbon emission. From the policy level, it is very important to control the emission during the production of Chinese-owned firms engaging in the non-processing trade goods production.

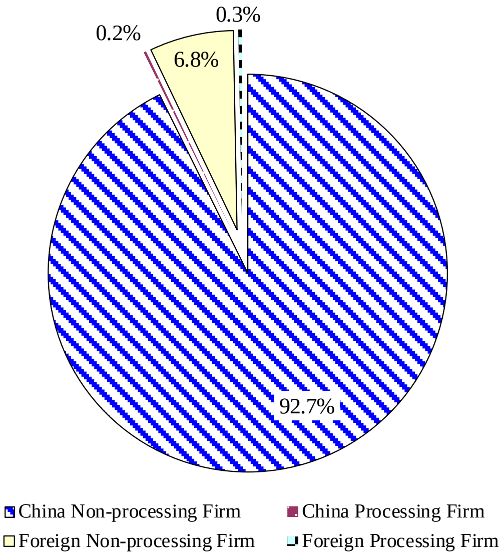


Figure 3 CO_2 emission distinguishing firm ownerships

From the industry level, industry with high carbon emissions of Chinese-owned firms and foreign-owned firms is different, and among most industries, emission of processing trade firms is smaller. Right half of the Figure 4 is the absolute value of emissions of firms with different ownerships in different industries, and left half is the proportion of emissions of different industries according to the ownerships of firms (relative value). According to the absolute value in the right half, we can draw two conclusions: (1) Industry with carbon emission of Chinese-owned firms mainly includes electricity and heat production and supply industry, metal smelting and rolling processing industry, chemical industry, non-metallic mineral product industry as well as transportation and post and warehousing industry. These industries are characterized by big capacity, are all high energy-consuming industry, so the carbon emission is relatively high. (2) Industry with carbon emission of foreign-owned firms mainly includes chemical industry, metal smelting and rolling processing industry, non-metallic mineral product industry, etc. Considering the factors such as energy security, China's market access threshold for energy production industry is higher. Therefore, foreign-owned firms mainly use the energy products of Chinese-owned firms for production. Industry with more emissions of foreign-owned firms also has relatively larger output and more energy consumption. It usually participates in international division of labor more deeply. According to relative value in the left half, we can draw two conclusions: (1) Industry of foreign-owned firms with larger proportion among total emissions mainly include communication equipment and other electronic equipment manufacturing industry, instrumentation and cultural office machinery manufacturing industry, textile, clothing, shoes and hats, leather, down feather and their products, and other light industry. (2) Industry of processing trade with larger proportion among total emissions mainly include instrumentation and cultural office machinery manufacturing industry, communication equipment and other electronic equipment manufacturing industry. This is mainly because these industries have more foreign-owned firms, and they are also labor-intensive export industries of China having comparative advantage in the international market.

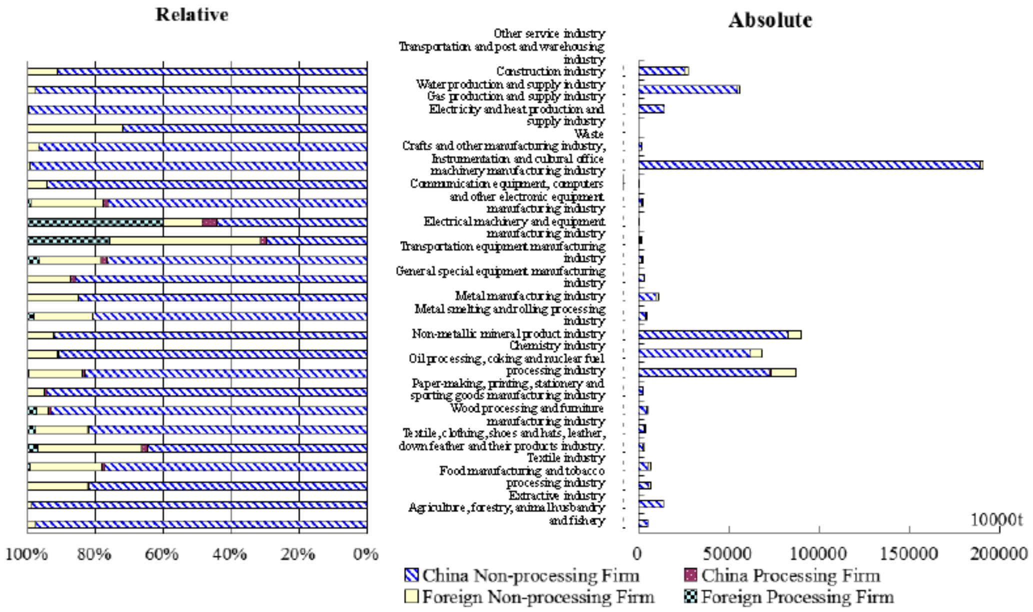


Figure 4 Carbon emissions of different industries and firms with different ownerships

3.2 Measurement of carbon emission intensity based on the firm heterogeneity information

If carbon emission intensity is defined as the carbon dioxide emissions from producing per unit of GDP, the carbon emission intensity of the firms in our country has very big difference based on firm ownerships. According to the first half of figure 5, carbon emission intensity of Chinese-owned firms engaging in the non-processing trade goods production is about 1.6 times of that of foreign-owned firms. Carbon emission intensity of Chinese-owned firms engaging in the processing trade goods production is about 3.9 times of that of foreign-owned firms. Carbon emission intensity of Chinese-owned firms engaging in the non-processing trade goods production is about 2.3 times of that of Chinese-owned firms engaging in the processing trade goods production. Carbon emission intensity of foreign-owned firms engaging in the non-processing trade goods production is about 5.6 times of that of foreign-owned firms engaging in the processing trade goods production. Carbon emission intensity of processing trade firms is relatively low, which is mainly determined by the production characteristic of processing trade firms. Processing trade firms are engaged in the processing of supplied materials or imported materials, intermediate input products are mainly from abroad, and use less energy input, so carbon emissions from energy consumption are relatively small. The reason why carbon emission intensity of foreign-owned firms is lower than that of Chinese-owned firms is because foreign-owned firms have relatively advanced production technology, and have better control technology in the process of production. It is worth noting that the dotted line in figure 5 refers to the national average level of carbon emission intensity measured by national table. It is not hard to find that because Chinese-owned firms engaging in the non-processing trade goods production has larger emission proportion, the average intensity measured by national table is close to the carbon emission intensity of such type of firm. From another point of view, average intensity measured by national table underestimates the carbon emission intensity of Chinese-owned firms engaging in the non-processing trade goods production, and also overestimates the carbon emission intensity of other three types of firms.

According to the upper half of figure 5, carbon emission intensity of Chinese-owned processing trade firms is much higher than that of foreign-owned processing trade firms. Although the production characteristics of processing trade firms decide its relatively low carbon emission intensity, why are there obvious differences between Chinese-owned firms and foreign-owned firms? We make further research on this issue. We calculated carbon emission intensity after removing chemical industry, as shown in the lower half of figure 5, both difference is remarkably reduced. The result is closer to our intuitive sense of processing trade firms. Meanwhile, the new result shows that carbon emission intensity of Chinese-owned firms engaging in the non-processing trade goods production is 4.5 times of that of Chinese-owned firms engaging in the processing trade goods production, and 4.8 times for foreign-owned firms. That is to say, after removing chemical industry, carbon emission intensity difference of processing and non-processing trade firms under the same ownership is basically the same (Explanation of formula sees appendix 1).

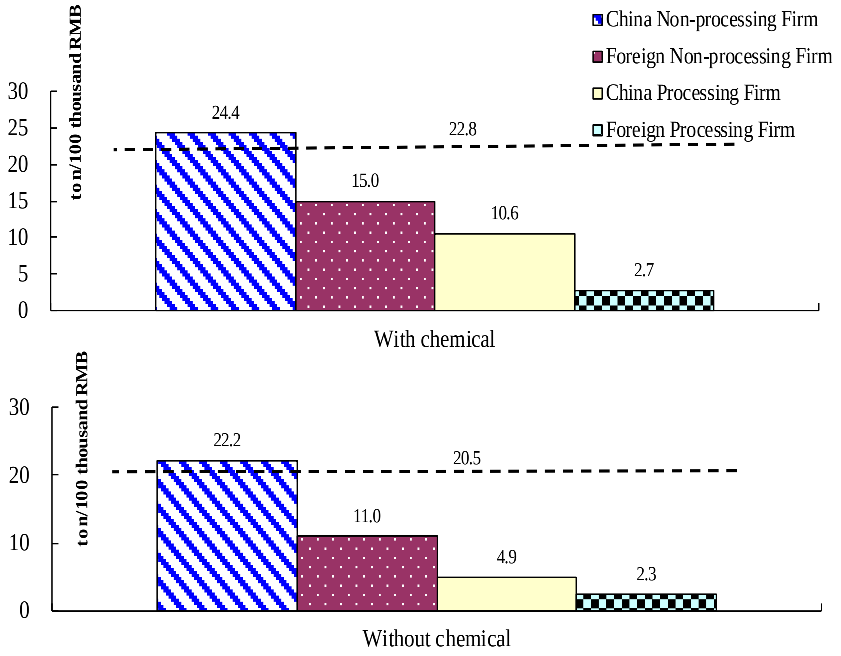


Figure 5 Unit carbon emission intensity of firms with different ownerships

3.3 Energy trading and carbon emissions among firms

Carbon dioxide emission mainly comes from energy consumption. Firms with different ownerships may use different types of energy sources, and these energy sources are from different energy supply companies. Table 3 is the matrix of carbon dioxide emissions of firms with different ownerships in 2007. Firms in the row (firms on the left side of table) are supplier of energy products, and firms in the column (header) are users of energy products. As you can see, energy products are mainly from firms engaging in the non-processing trade goods production and import. According to the sources of energy products used by firms with different ownerships, except Chinese-owned firms engaging in processing trade goods production, energy products used by other types of firms in the production process are mainly from Chinese-owned firms engaging in the non-processing trade goods production. For example, 92.5% of carbon emissions from the production process of Chinese-owned firms engaging in the non-processing trade goods production is due to the use of its own energy products. Such proportion of foreign-owned firms engaging in the non-processing trade goods production and the processing trade goods production is 93.1% and 66.3% respectively. In contrast, carbon emissions from the production process of Chinese-owned firms engaging in the processing trade goods production mainly come from the use of imported energy products, with the proportion of about 82.5%. It also explains why the carbon emission intensity of Chinese-owned firms engaging in the processing trade goods production is so high in chemical industry. Because, it is engaged in low added value and high emissions of primary chemical products processing (i.e., direct refining of primary chemical products through coal, oil, etc.).

Table 3 Supply and demand of energy products and carbon emissions

Unit: 10000t

Firm type	CN	CP	FN	FP	Total
CN	521709.3 （92.7%）	243.0 （17.0%）	38538.0 （93.1%）	1093.5 （66.3%）	561583.8 （92.5%）
CP	-	-	-	-	-
FN	17693.2 （3.1%）	8.3 （0.6%）	1333.3 （3.2%）	39.9 （2.4%）	19074.7 （3.1%）
FP	-	-	-	-	-
Import	23127.5 （4.1%）	1182.1 （82.5%）	1527.0 （3.7%）	515.9 （31.3%）	26352.4 （4.3%）
Total	562529.9 （100%）	1433.3 （100%）	41398.3 （100%）	1649.3 （100%）	607010.9 （100%）

With the results of table 3, we make the summary of the interest bound ship of carbon emission of firms with different ownerships conducting production activities in China from 4 aspects, sources of energy products used by the firm, product usage (for whom to produce and emit), place of carbon dioxide emission and ownership of production benefits (table 4). As you can see, (1) Energy sources used in the production process of Chinese-owned firms engaging in the non-processing trade goods production mainly comes from firms themselves, their products are supplied to the domestic and foreign markets (mainly to the domestic market), place of carbon dioxide emission is in China, and product benefits are obtained by Chinese-owned firms. Such ownership of Chinese-owned firms mainly use their national resources to provide products for their own country and the world, and also become China’s large carbon dioxide emitter when obtaining production benefits. (2) Energy sources used by Chinese-owned firms engaging in the processing trade goods production mainly come from import, their products are supplied to foreign countries, the carbon dioxide is to meet external demand, place of emission is in China, and processing fees are obtained by Chinese-owned firms. Such ownership of firms earn small processing fees by working for foreign countries, and use more foreign energy products, but leave carbon dioxide emissions at home. (3) Energy sources used by foreign-owned firms engaging in the non-processing trade goods production mainly come from China, their products are supplied to the world but the location of emission is China, and product benefits are obtained by foreign firms. Such ownership of foreign-owned firms make use of resources of China to make a profit but leave carbon dioxide emissions to China. (4) Energy sources used by foreign-owned firms engaging in the processing trade goods production mainly come from Chinese-owned firms, their products are supplied to foreign countries, the carbon dioxide is for foreign consumers but location of emission is China, and product benefits are obtained by foreign countries. Such ownership of firms make use of resources of China to process products for foreign consumers, get the processing gains but leave carbon dioxide emissions to China.

Table 4 Source and destination of energy, product, carbon dioxide emission and benefit

Table 4 Who Produce CO_2 Emissions for Whom

	Chinese owned Firm (Non-processing)	Chinese owned Firm (Processing)	Foreign-owned Firm (Non-processing)	Foreign-owned Firm (Processing)
Energy input mainly from	China	Foreign	China	China
Products (CO_2 emissions) for whom	China (main) and Foreign	Foreign	China and Foreign	Foreign
Where CO_2 emitted	China	China	China	China
Who earn the operation surplus	Chinese	Chinese	Foreigner	Foreigner

4. Influence of Firm Heterogeneity on the Measurement of Embodied Carbon

Production of any kind of products will use energy products, and these energy products will produce carbon emission in the process of combustion. Products will also use a lot of intermediate products in the process of production, and production process of intermediate products also will use energy and produce carbon emission. Such carbon dioxide producing in the whole industry chain due to the production of a particular product is often called as embodied carbon or carbon footprint. Embodied carbon emissions are mainly measured through input-output table. Based on IO model, Miller (1985) makes a definition of the forward industrial linkage and backward industrial linkage used in the upstream and downstream relationship of industry chain. With this definition, we put forward two kinds of indexes - forward industrial linkage -based embodied CO2 emissions and backward industrial linkage -based embodied CO2 emissions for the calculation method of embodied carbon to measure the embodied carbon for export or final use. Within them, backward industrial linkage -based embodied CO2 emissions refer to the carbon emissions of all the upstream industries directly and indirectly brought by a product's final demand or export in the industry chain. Forward industrial linkage based embodied CO2 emissions refer to the carbon emissions of a particular industry to meet the demands for intermediate products provided directly or indirectly by all the downstream industries. For example, car as the final product will need its upstream supplier in the industry chain in the process of production, such as the windshield, tires, engine and other nearly ten thousand kinds of parts. There will be a lot of carbon emissions in the production of these parts. Tire production needs the intermediate products provided by the rubber industry, and rubber will also produce carbon emissions in the process of its production. The production of a car will lead to the carbon emissions of all the upstream firms in the entire industry chain. This is the example of backward industrial linkage based embodied CO2 emissions. By measuring the backward embodied carbon, we can easily know which products' industry chain is more energy-consuming or more environmentally friendly. About the forward industrial linkage based embodied CO2 emissions; the power industry is a good example. In the power industry, especially the thermal power generation will produce a lot of carbon emissions in the production of electric power products. These power products are supplied to its downstream firms, such as tire manufacturer and metal products manufacturer. When the tire installed on the car and metal parts installed on the phone are exported, value of the electric power products actually has directly and indirectly converted to these export products. Meanwhile, the carbon emissions of power industry also have been embodied in these export commodities. Forward industrial linkage-based embodied CO_2 emissions and different industries of GDP of national economic accounting are completely corresponding concept. With it, we can easily know how many the environmental cost of added value of one industry is when it is exported through the downstream industry chain in the form of various products.

Measurement method of backward and forward industrial linkage-based embodied CO_2 emissions is as shown in formula (5) and formula (6) respectively.

Backward industrial linkage-based embodied CO_2 emissions

$$C_i^B = B \cdot X_i = c \cdot L \cdot X_i = \begin{pmatrix} c_1 & c_2 & \cdots & c_n \end{pmatrix} \cdot \left(I - A_d\right)^{-1} \cdot \begin{pmatrix} 0 \\ \vdots \\ f_i \\ \vdots \\ 0 \end{pmatrix} \qquad （5）$$

Forward industrial linkage-based embodied CO_2 emissions:

$$C_j^F = B_j \cdot X = c_j \cdot L \cdot X = \begin{pmatrix} 0 & \cdots & c_j & \cdots & 0 \end{pmatrix} \cdot \left(I - A_d\right)^{-1} \cdot \begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{pmatrix} \qquad （6）$$

Where, C_i^B is vector of backward industrial linkage-based embodied CO_2 emissions of i product, C_j^F is vector of forward industrial linkage-based embodied CO_2 emissions of j industry, $B = c \cdot L$, $c = \begin{pmatrix} c_1 & c_2 & \cdots & c_n \end{pmatrix}$ is column vector of direct carbon emissions under the unit output, c_j is carbon dioxide emissions of j industry under the unit output, $L = \left(I - A_d\right)^{-1}$ is domestic Leontief Inverse matrix, I

is unit matrix, A_d is domestic direct consumption coefficient matrix, $F = \begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{pmatrix}$ is export or final use, f_i is export or final use of industry i.

When calculating the embodied carbon of different industries, due to the different connotations and calculation methods of forward and backward industrial linkage-based embodied CO_2 emissions, their calculation results are also different. There is no difference between two in the definition when the industry is aggregated to the national value. Reason is very simple, as shown in formula (5) and (6), if aggregating i and j respectively, the result is same. Aggregation of embodied carbon of all the upstream firms caused by a product is always same with that of embodied carbon of all the downstream industries provided by one industry. Although total embodied carbon emissions have nothing to do with measurement method (forward or backward industrial linkage-based), there is an obvious difference between the results calculated by firm table and traditional national table. As shown in figure 6, the embodied carbon for export in national table is 1.9043 billion tons, while embodied carbon for export in firm table is 1.586314 billion tons. The calculation result of the national table is 20.0% higher than that of the firm table. This is mainly because the national table only reflects the average production, energy conservation and emission reduction technology of firms with different ownerships of one industry, which has large difference from the information contents in the firm table. That’s why national table overestimates the embodied carbon for export. Specifically, the measurement results of embodied carbon for export in the national table and firm table show that carbon emissions for final use in the national table is 4.378599 billion tons, and in the firm table is 4.698782 billion tons.

With firm table as the true value, national table overestimates 6.8% of embodied carbon for export. Also it underestimates 6.8% of embodied carbon for final domestic demand.

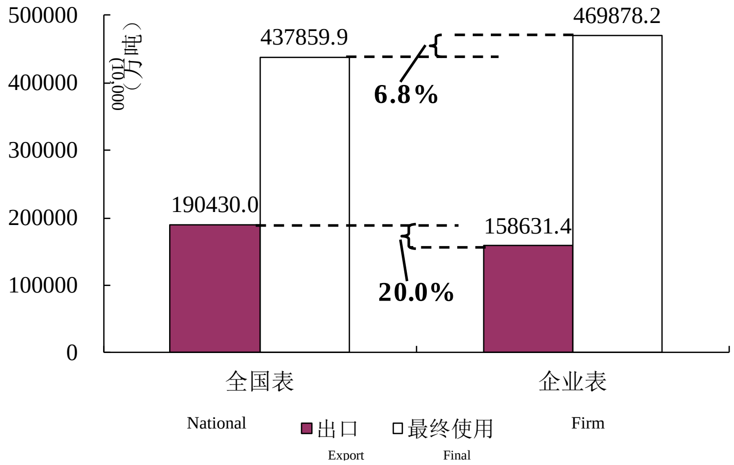


Figure 6 Embodied carbon for export and final demand in the national table and firm table

It shall be noted that using the standardized method of taking the final demand of different industries in the input-output table as 1 to calculate the embodied carbon can compare the carbon emissions brought by different firms due to the same change in demand. As shown in figure 7, when the final demand is taken as 1, the backward industrial linkage based embodied CO_2 emissions of Chinese-owned firms engaging in the non-processing trade goods production, foreign-owned firms engaging in the non-processing trade goods production, Chinese-owned firms engaging in the processing trade goods production and foreign-owned firms engaging in the processing trade goods production are 0.0095, 0.0066, 0.0012 and 0.0008 respectively. Similarly, the dotted line in figure 7 is the average (0.008) without distinguishing firm types and calculated by the national table. Therefore, if we only use the national table to measure embodied carbon, Chinese-owned firms engaging in the non-processing trade goods production will be underestimated, other types of firms will be overestimated.

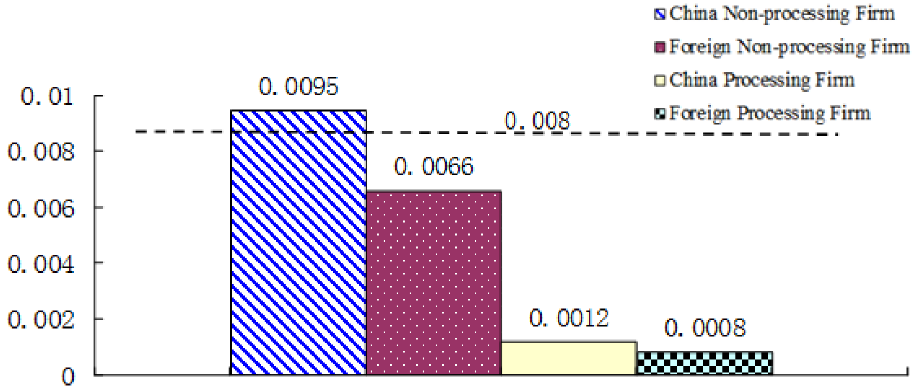


Figure 7 Carbon emissions brought by the unit final demand change

From the perspective of industry sectors, the measurement result of embodied carbon emissions not only depends on calculation method (forward and backward), but also relates to whether the firm heterogeneity is distinguished in the input-output table. Figure 8 and figure 9 are forward and backward industrial linkage based embodied CO_2 emissions of different industries in 2007 respectively. Contrasting these two figures, we can find that though the total value of embodied carbon of different industries is same but the embodied carbon structure of specific industries is different. As shown in figure 8, the industry with larger forward industrial linkage based embodied CO_2 emissions includes electricity and heat production and supply industry, metal smelting and rolling processing industry, and chemical industry. But as shown in figure 9, the industry with larger backward industrial linkage based embodied CO_2 emissions includes construction industry, service industry, general special equipment manufacturing industry, etc. From the perspective of intermediate product providers (forward), the emission reduction shall focus on such big emitters in the upstream of industry chain, such as electricity and heat production and supply industry, metal smelting and rolling processing industry, and chemical industry. From the perspective of the intermediate product demander, the emission reduction shall focus on the firms in the downstream of industry chain, such as construction industry, service industry and general special equipment manufacturing industry. If downstream firms require supplier's products to be more environmentally friendly, it will drive the greenization of the whole supply chain. That's the core concept of the so-called green supply chain we often mention. Experience of GE and Wal-Mart also proves its effectiveness in the practice of low carbon emission reduction (Zhang Changhui, 2009, Wang Xianzhi, 2009, Zhang Qiutong, 2011).

In addition, contrasting figure 8 and figure 9, we also can find two similarities and differences. (1) Total forward industrial linkage based embodied CO_2 emissions of all the industries in figure 8 are less affected by the firm heterogeneity, and there is only difference in embodied carbon for export and final use. For backward industrial linkage based embodied CO_2 emissions as shown in figure 9, measurement results of chemical industry, construction industry and service industry between national table and firm table have obvious difference. The above fact shows that error distribution with forward linkage measuring embodied carbon is more homogeneous. (2) Whether forward industrial linkage based embodied CO_2 emissions or backward industrial linkage based embodied CO_2 emissions, embodied carbon for export of most industries in the national table is more than that in the firm table, while embodied carbon for final use in the national table is less than that in the firm table.

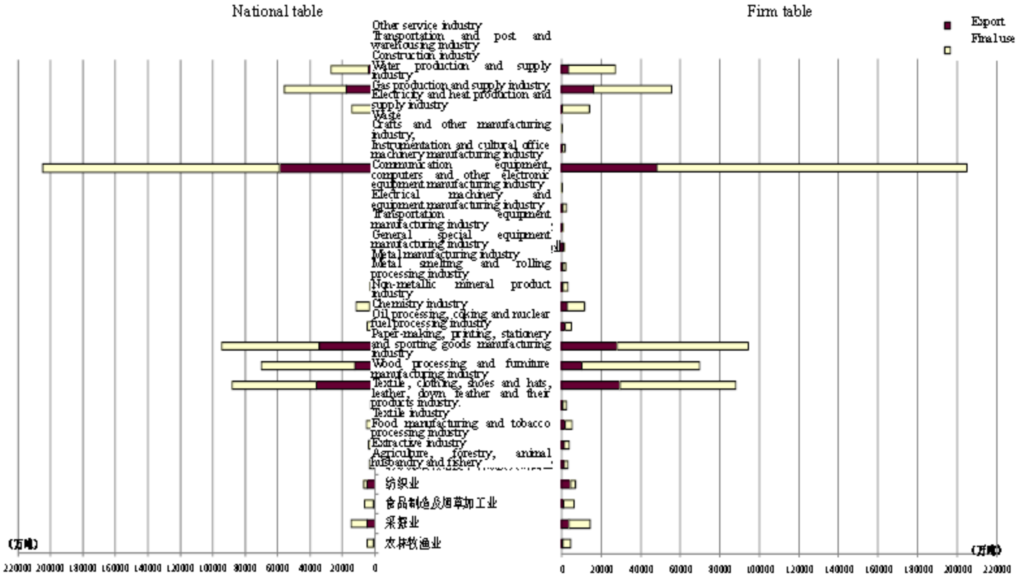


Figure 8 Forward industrial linkage based embodied CO2 emissions of different industries in the national table and firm table

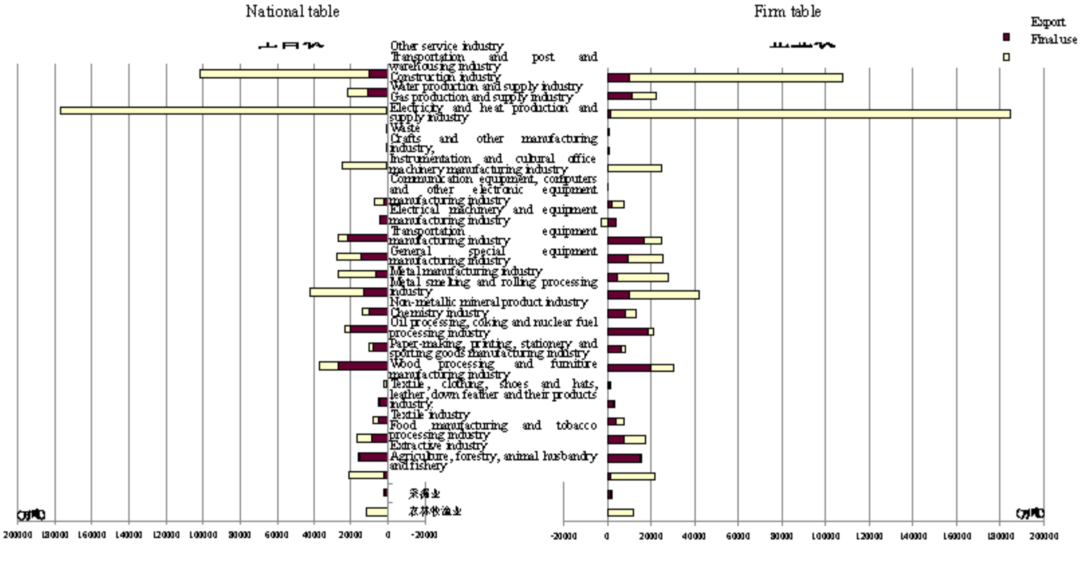


Figure 9 Backward industrial linkage based embodied CO2 emissions of different industries in the national table and firm table

Since the firm table reflects production technology and technical characteristics of energy saving and emission reduction of the firms with different ownerships, the embodied carbon calculated based on it is more accurate and reasonable than that based on national table. By comparing the percentage difference of calculating the embodied carbon in firm table and national table (with measurement results of national table as the standard), we can obtain the results as shown in figure 10 and figure 11. It’s evident that influence of the type of input-output table on forward and backward embodied carbon mainly reflects the following characteristics: (1) The calculation result of embodied carbon (including forward and backward industrial linkage based embodied CO_2 emissions) for final use in the firm table is higher than that in the national firm, and calculation result of forward embodied carbon for export in the firm table is lower than that in the national table. Except gas production and supply industry, water production and supply industry, construction industry, transportation, post and warehousing industry, and service industry, calculation result of backward embodied carbon for export in the firm table is lower than that in the national table. (2) There is small inter-industry difference in measuring forward industrial linkage based embodied CO_2 emissions for export in the firm table and national table. There is obvious difference in measuring forward industrial linkage based embodied CO_2 emissions for final use, which is mainly reflected in communication equipment, computer and other electronic equipment manufacturing industry, instrumentation and cultural office machinery manufacturing industry. (3) There is big intra-industry difference in measuring backward industrial linkage based embodied CO_2 emissions for export and final demand in the firm table and national table For carbon emissions of the whole industry chain brought by the domestic final use of communication equipment, its measurement result in the firm table is about 70% larger than that in the national table. And for carbon emissions of the whole industry chain brought by the export of communication equipment, the result in the firm table is 20% lower than that in the national table. The conclusion above fully shows that when calculating the embodied carbon, the firm heterogeneity information is indispensable. Otherwise, it will cause great overestimate or underestimate at the industry level.

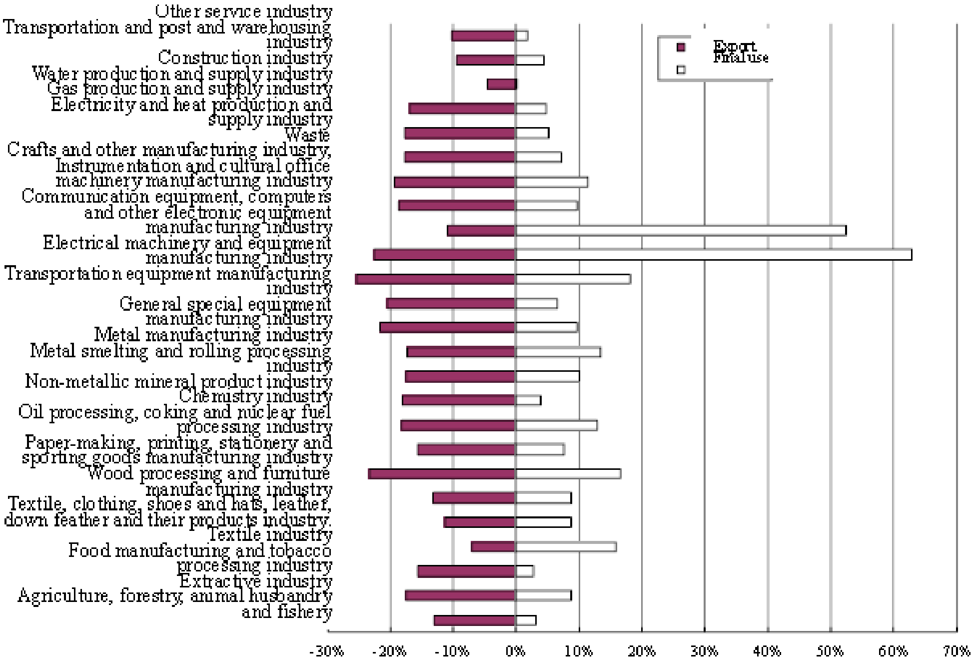


Figure 10 Comparison of forward industrial linkage based embodied CO2 emissions in the national table and firm table

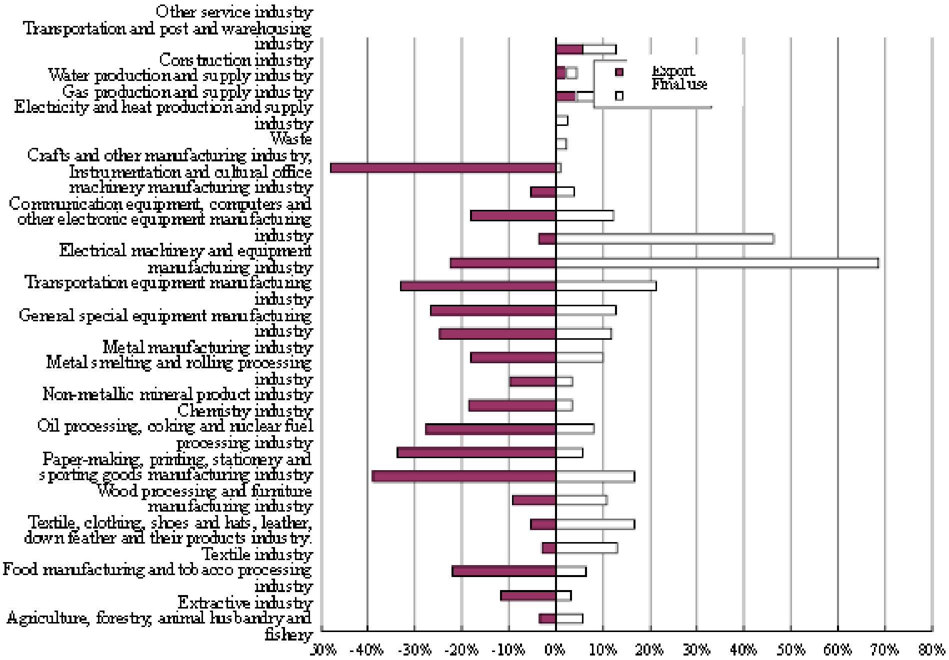


Figure 11 Comparison of backward industrial linkage based embodied CO2 emissions in the national table and firm table

We introduce the traditional concept of carbon emission intensity in the last chapter. It refers to the carbon emissions brought by unit output of industry in the process of production or GDP. It can only reflect the environmental costs of one industry or firm. It cannot reflect the environmental costs of industry chain including its upstream and downstream. Here we make use of the unique advantages of input-output table, draw a analogy with definition of “embodied carbon”, introduce the concept of “embodied GDP”, and use the ratio of “embodied carbon” to “embodied GDP” to represent the carbon emission intensity in the industry chain, namely, the concept of Embodied Carbon Emission Intensity (ECEI). This new concept gives good reference information to define whether industry chain is environmentally friendly or high-carbon.

To explore more significance of firm heterogeneity, we give full play to the advantage of input-output analysis; we use the matrix to present the relationship between embodied GDP and embodied carbon from export of firms with different ownerships. As shown in table 5, look from the export product production firms (firms in the header), GDP brought by the exports of Chinese-owned firms to the whole industry chain is 3.5481 billion Yuan, around 57% of overall GDP. Most of GDP are created by Chinese-owned firms. GDP brought by the exports of foreign-owned firms also cannot be ignored. Account for around 37% of overall GDP. Effect of Chinese-owned non-processing trade firms' exports promoting GDP is small, only 6% of overall GDP. It is noteworthy that foreign-owned non-processing trade firms' exports mainly promote Chinese-owned firms' GDP (10%) and foreign-owned firms' GDP (7%). The former is bigger, which is mainly because Chinese-owned firms are the major supplier in the production chain of foreign-owned non-processing trade firms' exports. GDP created by Chinese-owned firms promoted by foreign-owned processing trade exports is 9%, by foreign-owned non-processing trade firms is 2%, and by themselves is 10%. As you can see, both Chinese-owned firms and foreign-owned firms participate in the production process of foreign-owned firms engaging in processing trade goods production, and the contribution of Chinese -owned firms is more. From the perspective of intermediate product supplier (firms on the left side of the table), 75% of GDP promoted by China's exports is created by Chinese-owned firms engaging in non-processing trade goods production, and 13%, 10% and 2% are respectively created by foreign-owned firms engaging in non-processing trade goods production, foreign-owned firms engaging in processing trade goods production and Chinese-owned firms engaging in processing trade goods production.

Above is the embodied GDP for export. The embodied carbon emission for export can also be made by similar measurement. The main results are as shown in table 6. By contrasting the result in table 5, we can find that carbon emissions brought by export of firms with different ownerships mainly come from Chinese-owned firms engaging in non-processing trade goods production. Besides the reason that such ownership of Chinese-owned firms are the main intermediate products supplier of all kinds of export firms, and too high carbon emission intensity in the production process is another reason.

Table 5 GDP promoted by exports of firms with different ownerships

(0.1 billion Yuan)	CN	CP	FN	FP	Total
CN	32,806	2,229	6,499	5,384	46,918
CP	0	1,355	0	0	1,355
FN	2,675	134	4,325	1,023	8,157
FP	0	0	0	6,099	6,099
Total	35,481	3,718	10,824	12,505	62,529
CN	52%	4%	10%	9%	75%
CP	0%	2%	0%	0%	2%
FN	4%	0%	7%	2%	13%
FP	0%	0%	0%	10%	10%
Total	57%	6%	17%	20%	100%

Table 6 Embodied carbon matrix promoted by exports of firms with different ownerships (ten thousand tons of CO_2)

	CN	CP	FN	FP	Total
CN	97,834	4,369	22,338	18,578	143,119
CP	0	1,433	0	0	1,433
FN	4,833	222	7,392	1,417	13,863
FP	0	0	0	1,649	1,649
Total	102,667	6,024	29,729	21,644	160,065
CN	61%	3%	14%	12%	89%
CP	0%	1%	0%	0%	1%
FN	3%	0%	5%	1%	9%
FP	0%	0%	0%	1%	1%
Total	64%	4%	19%	14%	100%

If dividing embodied carbon for export by embodied GDP for export, we can get the new index of embodied carbon emission intensity as shown in table 7. The index shows that how much the firm needs to pay for carbon emissions in order to get a unit GDP by exporting. Obviously, compared to the national average (26000 tons/one billion Yuan), embodied carbon emission intensity of Chinese-owned firms engaging in the non-processing trade goods production brought by foreign-owned firms is the highest, 3.5 and 3.4 respectively. This mainly explains that the foreign-owned firms in the upstream industry chain of China are high-carbon. Embodied carbon emission intensity (3.0) of upstream similar firms brought by Chinese-owned firms engaging in the non-processing trade goods production is higher than the national average. Other types of embodied carbon emission intensity are lower than the national average. Above results clearly demonstrates that foreign-owned firms have less emission in the process of production of export products, but carbon emission intensity of upstream

Chinese-owned firms engaging in non-processing trade goods production promoted by them is the strongest. Chinese-owned firms engaging in non-processing trade goods production have a lot of emissions in the production of export products, and emissions of upstream Chinese-owned firms promoted by them are higher than the national average. From the perspective of green supply chain management, responsibility of export products producer shall not be ignored. From the perspective of suppliers providing intermediate products for the production of export products, their responsibility for energy conservation and emission reduction is also very big.

Table 7 Embodied carbon emission intensity coefficient of firms with different ownerships (ten thousand tons/one billion Yuan)

	CN	CP	FN	FP	Total
CN	3.0	2.0	3.4	3.5	3.1
CP	-	1.1	-	-	1.1
FN	1.8	1.7	1.7	1.4	1.7
FP	-	-	-	0.3	0.3
Total	2.9	1.6	2.7	1.7	2.6

5. Conclusions and Policy Suggestions

This paper uses 2007 input-output table of firms with different ownerships in China to measure the direct emissions, carbon emission intensity, embodied carbon emissions and embodied carbon emission intensity of different industries. Meanwhile, we make the comparative analysis on the differences in measuring the above index by the traditional national input-output table and input-output table of firms with different ownerships and its reasons. Main conclusions can be summarized as follows: (1) There are significant differences in contribution of China’s total carbon emissions of firms with different ownerships. More than 90% of China’s carbon dioxide emissions in 2007 is from Chinese-owned firms engaging in non-processing trade goods production. And emissions proportion of other firms is small. From the nature of the firm, emissions of Chinese-owned firms are far more than that of foreign-owned firms, and emissions of non-processing trade firms are far more than processing trade firms. Above results depend on the scale of production of the firm, and the more important reason is the difference in carbon emission intensity of the firm. Our measurement results show that carbon emission intensity of Chinese-owned firms engaging in the non-processing trade goods production is about 1.6 times of that of foreign-owned firms. Carbon emission intensity of Chinese-owned firms engaging in the processing trade goods production is about 3.9 times of that of foreign-owned firms. Carbon emission intensity of Chinese-owned firms engaging in the non-processing trade goods production is about 2.3 times of that of Chinese-owned firms engaging in the processing trade goods production. Carbon emission intensity of foreign-owned firms engaging in the non-processing trade goods production is about 5.6 times of that of foreign-owned firms engaging in the processing trade goods production.

(2) At the industry level, except the department of energy production, industry with high emission of both Chinese-owned firms and foreign-owned firms is basically same, including metal smelting and rolling processing industry, chemical industry, non-metallic mineral product industry and other high energy-consuming industries. If according to the carbon emission intensity of different industries, carbon emission intensity of Chinese-owned firms engaging in processing trade goods production of chemical industrial products is more than foreign-owned firms. This is mainly because they are engaged in low value added and high emissions of primary chemical productions.

(3) We also make the analysis on the interests of carbon emission of firms with different ownerships conducting production activities in China from 4 aspects, sources of energy products used by the firm in the production process, product consumer, and place of carbon dioxide emission and ownership of production benefits. It is obvious that Chinese-owned firms engaging in non-processing trade mainly use their national resources to provide products for their own country and the world, and also become China's big carbon dioxide emitter when obtaining production benefits. Chinese-owned firms engaging in processing trade earn small processing fees by working for foreign countries, and use more foreign energy products, but leave carbon dioxide emissions at home. Foreign-owned firms engaging in non-processing trade make use of resources of China to make a profit but leave carbon dioxide emissions to China. Foreign-owned firms engaging in processing trade make use of resources of China to process products for foreign consumers, get the processing gains but leave carbon dioxide emissions to China.

(4) Firm heterogeneity information is important and indispensable for the measurement of embodied carbon emissions. Our measurement results show that ignoring the firm heterogeneity will make the embodied carbon for export is overvalued 20%, and embodied carbon for final demand is undervalued about 6.8%. At the industry level, the error will be more obvious. Measurement error of embodied carbon for final demand in the communication equipment industry even reaches 70%, and embodied carbon for export in the printing industry reaches 40%. This is mainly because production of products for final demand directly and indirectly use more intermediate products provided by Chinese-owned firms engaging in the non-processing trade goods production, and export products is caused by processing trade of low carbon emission to

a great extent.

(5) After we introduce the new index - embodied carbon emission intensity, the results measured by the firm table show that foreign-owned firms have few emissions in the process of production of export products, but carbon emission intensity of upstream Chinese-owned firms engaging in non-processing trade goods production promoted by them is the strongest. Chinese-owned firms engaging in non-processing trade goods production have a lot of emissions in the production of export products, and emissions of upstream Chinese-owned firms promoted by them are higher than the national average. From the perspective of green supply chain management, responsibility of export products producer shall not be ignored. From the perspective of suppliers providing intermediate products for the production of export products, their responsibility for energy conservation and emission reduction is also very big.

There are several policy suggestions: 1) Though China is a big exporter, we shall not blindly emphasize the promotion of export to China’s carbon emissions, but pay more attention to the promotion effect of domestic demand. Our measurement results show that the traditional measurement results of ignoring firm heterogeneity will overestimate carbon emissions promoted by export and underestimate the carbon emissions brought by domestic demand. Therefore, we shall take how to guide the greenization of domestic demand structure as the basis. 2) The traditional high energy-consuming enterprises are still the major part of the emissions, and energy efficiency is far lower than the foreign-owned firms. Laws and regulations and market mechanism shall be used simultaneously, and enterprises shall be guided to improve energy efficiency so as to make industrial structure more reasonable and environmentally friendly. 3) We shall not take the old road of foreign-owned firms putting the step of high carbon emissions in the industry chain in developing countries, encourage Chinese-owned firms wanting to be bigger and stronger to introduce and explore the mechanism of green supply chain management, improve the environmental protection consciousness of organizers of industry chain, and promote the emission reduction of upstream firms at home and abroad.

Appendix 1 Contribution decomposition of chemical industry in Chinese-owned and foreign-owned firms' processing trade intensity

Decomposition formula of carbon emission intensity about chemical industry and non-chemical industry:

$$IN = \frac{C}{V} = \frac{C_1 + C_2}{V} = \frac{C_1}{V_1} \times \frac{V_1}{V} + \frac{C_2}{V_2} \times \frac{V_2}{V} = IN_1 \times g_1 + IN_2 \times g_2$$

Where, IN is carbon emission intensity of one ownership of firm, C is carbon dioxide emissions of such ownership of firm, V is GDP created by such ownership of firm, 1 represents chemical industry, 2 represents non-chemical industry, C_i ($i = 1,2$) is the industry i's carbon dioxide emissions, V_i ($i = 1,2$) is the industry i's GDP, IN_i ($i = 1,2$) is the industry i's carbon emission intensity, g_i ($i = 1,2$) is the proportion of the industry i's GDP of total GDP.

Carbon emission intensity of Chinese-owned firms and foreign-owned firms engaging in the processing trade is calculated respectively according to the formula, and we can find that there are two main factors leading to the regularization of carbon emission intensity: one is the difference in the carbon emission intensity of different firms in chemical industry and non-chemical industry, and the other is the difference in the scale of GDP of different firms in chemical industry and non-chemical industry. According to the measurement results of carbon intensity, carbon emission intensity of non-chemical industrial products of Chinese-owned firms engaging in the processing trade is 4.9 tons/one billion Yuan, and of foreign-owned firms is 2.3 tons/one billion Yuan, differing more than 2 times. Carbon emission intensity of chemical industrial products of Chinese-owned firms engaging in the processing trade is 54.9 tons/one billion Yuan, and of foreign-owned firms is 8.3 tons/one billion Yuan, differing about seven times. According to the measurement results of GDP proportion, GDP created by

Chinese-owned firms engaging in the processing trade in the chemical industry is 11.46% of its total GDP, and of foreign-owned firms is only 6.4%.

We make the analysis on the causes of generating above two factors: there is the second factor in reality, so there is no need to make explanation. The first factor is mainly due to the relatively low efficiency in energy conservation and emissions reduction of China’s processing trade in the process of production, and there is more primary processing trade, with low product unit value. Therefore, carbon emission intensity of Chinese-owned firms’ processing trade is greater than that of foreign-owned firms’ processing trade.

References

[1]. Lenzen M. Primary Energy and Greenhouse Gases Embodied in Australian Final Consumption: An Input-output Analysis [J]. Energy Policy, 1998,26 (6):495-506.

[2]. 刘红光，刘卫东，唐志鹏，范晓梅．中国区域产业结构调整的 CO_2 减排效果分析——基于区域间投入产出表的分析[J]．地域研究与开发，2010，29（3）：129-135．

[3]. 何艳秋．行业完全碳排放的测算及应用[J]．统计研究，2012，29（3）：67-73．

[4]. 孙建卫，陈志刚，赵荣钦，黄贤金，赖力．基于投入产出分析的中国碳排放足迹研究[J]．中国人口·资源与环境，2010，20（5）：28-34．

[5]. Schaeffer R, de Sá A L. The embodiment of carbon associated with Brazilian imports and exports [J]. Energy Conversion and Management, 1996, 37(6): 955-960.

[6]. 张友国．中国贸易含碳量及其影响因素-基于（进口）非竞争型投入产出表的分析[J]．经济学季刊，2010，9（4）：1287-1310．

[7]. Machado G, Schaeffer R, Worrell E. Energy and carbon embodied in the international trade of Brazil: an input–output approach [J]. Ecological economics, 2001, 39(3): 409-424.

[8]. 陈迎，潘家华，谢来辉．中国外贸进出口商品中的内涵能源及其政策含义[J]．经济研究，2008，7：11-25．

[9]. Weber C L, Matthews H S. Embodied environmental emissions in US international trade, 1997-2004[J]. Environmental Science & Technology, 2007, 41(14): 4875-4881.

[10]. Nakano S, Okamura A, Sakurai N, et al. The measurement of CO_2 embodiments in international trade: evidence from the harmonised input-output and bilateral trade database[R]. OECD Publishing, 2009.

[11]. Peters G P, Hertwich E G. CO_2 embodied in international trade with implications for global climate policy[J]. Environmental Science & Technology, 2008, 42(5): 1401-1407.

[12]. 刘红光，刘卫东，唐志鹏．中国产业能源消费碳排放结构及其减排敏感性分析[J]．地理科学进展，2010（6）：670-676．

[13]. Meng B, Fang Y, Yamano N, et al. Measuring global value chains and regional economic integration: an international input-output approach [J]. 2012.

[14]. Ahmad Nadim and Sonia Araujo, “Using Trade Micro data to Improve Trade in Value Added Measures: Proof of Concept Using Turkish Data”. OECD Working paper. 2011

[15]. Feenstra Robert and Branford Jensen. “Evaluating Estimates of Materials Offshoring from U.S. Manufacturing”, Economics Letters. 2012. vol. 117(1):170-173.

[16]. Kee, Hiau Looi, and Heiwai Tang. “Domestic Value Added in Chinese Exports”, Tufts University, mimeo. 2012.

[17]. Koopman, Robert, Zhi Wang and Shang-jin Wei. “Estimating Domestic Content in Exports When Processing Trade is Pervasive”, Journal of Development Economics. 2012

(99): 178-189.

[18]. Hong Ma,Zhi wang, and Kunfu Zhu, “Domestic Content in China's Exports and its Distribution by Firm Ownership” . 2014.

[19]. 张昌辉. 上海通用汽车：“绿动”铸就核心竞争力[N]. 第一财经日报,2009-10-30.

[20]. 张秋彤.沃尔玛的绿色供应链管理[J].中国市场, 2011(02).

[21]. 王先知,李天辰.沃尔玛:携手供应商打造绿色供应链[J].WTO 经济导刊,2009(03).

Chapter 5

The Emission Reduction Effect and Economic Impact of an Energy Tax vs. a Carbon Tax in China: A Dynamic CGE Model Analysis

Lele ZOU[1], Jinjun XUE[2], Alan FOX[3], Bo MENG[4], Tsubsa SHIBATA[4]

Abstract: Chinese leader Xi Jinping announced during a meeting with President Barack Obama at the Peking APEC Summit that China will be expected to reach its peak carbon emissions before 2030. This is the first time the Chinese government stated a hard target (not a soft target such as intensity reduction) for reducing CO2 emissions. To meet the target, China intends to undertake more serious measures and implement new policies to limit the total volume of emissions. The new policies under discussion include a carbon tax, an energy tax, an emissions trading scheme (ETS), and cap-and-trade systems. Using a CGE model, this study conducts simulation studies on the functions of an energy tax and a carbon tax and analyzes their effects on economic growth and employment in China as well as their impacts on the energy intensive sectors in different scenarios. We found that the Chinese economy is affected at an acceptable level by the two taxes. GDP will lose less than 0.8% with a carbon tax of 100, 50, or 10 RMB/ton CO2 or 5% of the delivery price of an energy tax. Thus, the loss of real disposable personal income is smaller. Compared with implementing a single tax, a combined carbon and energy tax induces more emission reductions with relatively smaller economic costs. With these taxes, the import and export of energy intensive industries are changed, leading to improved domestic competitiveness. We further show that for China, the sooner such taxes are launched, the smaller the economic costs and the more significant the achieved emission reductions.

Keywords: Energy tax, Carbon tax, Climate change, CGE model, Energy intensive industry

JEL classification: C13, C15, C54, E37, J21, K32, O44, Q54

1: Associate professor, Institute of Policy and Management, Chinese Academy of Sciences, China

2: Professor, School of Economics, Nagoya University, Japan

3: International Economist, USITC, the USA (**The views in the paper are those of the authors and may not reflect the views of the USITC and its Commissioners or any other organization that the authors are affiliated with**)

4: Research Fellow, IDE-JETRO, Japan

Acknowledgement: This study is funded by the CIDEG-IDE/JETRO-USITC-IGLCE Joint Project, the Chinese National Scientific Fund No. 71173206 and the Chinese National Support Fund 2012BAC20B12. We are grateful to Economic Research Center of Graduate School of Economics, Nagoya University for providing the opportunity to conduct a joint research from April 1st to October 2, 2014. In addition, we thank Dr. Masami ISHIDA (Director-General, Development Studies Center, IDE-JETRO) for his helpful comments on the paper.

1. Introduction

The Chinese government made a commitment at the COP19 in 2009 to reduce CO2 intensity by 40–45% from 2005 levels by 2020. The commitment was incorporated into its 12th Five-year Plan (State Coucil 2012) issued in 2011, through the dual reduction targets of 16% for CO2 and 17% for energy intensity by 2015. Nonetheless, China's total volume of CO2 emissions has been rapidly increasing. To meet this international commitment and reach a concrete accomplishment of the planned targets, the Chinese leader, Xi Jinping, made an announcement during a meeting with President Barack Obama that China will likely reach its carbon emissions peak before 2030. This is an important signal showing that China will take more serious measures to control total emissions.

However, China is currently facing serious challenges of slowing economic growth and inefficient energy use. To form a concrete plan and shape an efficient policy, China needs to carry out more research on how to achieve the targets, what will be the most efficient policy, and what sort of technology should be used.

Many policy instruments have already been implemented; however, most of them are not efficient. To foster new thinking about policies under Xi's administration, in recent years a number of different economic instruments have been widely discussed. Carbon and energy taxes, an emissions trading scheme (ETS), and a cap-and-trade system are some examples. Using a CGE modeling approach, this study focuses on environmental and carbon taxes policies by analyzing their effectiveness in reducing carbon emissions while maintaining economic growth and employment in China.

The study is organized as follows. Section 2 provides a literature review; section 3 explains the contents of the environment and carbon taxes. Section 4 compares the different impacts of the two taxes on the Chinese economy; and section 5 presents a brief conclusion.

2. Research review

China has no specific separated tax category for energy, rather a value added tax for energy selling, a consumption tax for energy use, and a resource tax for energy exploration (see Appendix 1). In this study, the term “energy tax” refers to the tax levied on energy sources as commodities and is thus close to the existing “resources tax.”

Resources taxes were first implemented in 1994, which covered seven categories of resources: crude oil, natural gas, raw coal, ferrous metals ore, nonferrous metals ore, other non-metal ores, and salts. These taxes were based on the amount. For example, the taxes for crude oil, raw coal, and natural gas were 14–30 RMB/ton, 0.3–2.4 RMB/ton, and 7–15 RMB/thousand cubic meters, respectively. Because of the fixed low taxation rates and the amount based collection, which accounted for only 0.61% in the total national taxation income (Ifeng 2010), resources taxes were unable to reflect the environmental costs and price fluctuations. In 2009, the fuel tax was launched, which was expected to be more effective in adjusting the use of resources. Since 2010, resource taxes gradually changed into price-based ones, first in China’s western regions, followed by the eastern regions; the tax rates for crude oil and natural gas have been set at 5% of the delivery price. However, due to the large proportion of coal in the energy structure—70% share of total energy use and about 80% of power generation—it was not included in the tax. In many other countries, an energy tax has been applied for decades, which is called fuel tax in most cases. Of these taxes, the most basic categories are an ad valorem duty and a specific duty. Because of the different yields and costs of different kinds of fuels, fuel taxes are becoming increasingly detailed in practice. In 2014, the proposed fuel tax under debate in the European Union (EU) focuses on returning to carbon and energy composition-based taxing with an additional floor rate to debate emissions from diesel, whereas the current one is based on amount of consumed fuels.

Numerous researches have been conducted on fuel tax-related issues from various aspects. For example, regarding the mechanism of the economy and politics (Hammar, Löfgren et al. 2004; Sterner 2007), the relationship with other taxes or fees (Parry and Small 2005; Zhou, Levine et al. 2010), their effectiveness in saving energy and reducing emissions (Bartocci and Pisani 2013; Mazumder 2014), and their impacts on national- or household-scale economies (Sterner 2012; Haufler and Mardan 2014; Jiang and Shao 2014), etc.

Fossil fuel conservation is not the only issue of concern to China. Greenhouse gas emissions control is another huge and urgent challenge. A carbon tax has been under consideration for several years now in China. Some argue that a carbon tax is more effective than an energy tax in reducing CO2 emissions while simultaneously reducing energy consumption. For example, Li (2003) uses an econometric model to analyze China's energy use under a carbon tax of 36.70 CNY/ton CO2 and concluded that in 2030, such a tax would reduce China’s CO2 emissions by 9.3% while reducing primary energy consumption by 7.3% compared with 2010 (Li 2003). Jiang et al. (2009) conducts a similar analysis, but extends the time scale to 2050 (Jiang, Hu et al. 2009). However, this study contains no implementation of a pure carbon tax; some researchers prefer to treat it as a resource tax because a carbon tax most closely relates to emissions, while others argue that it should be categorized as a specific tax because it is based on the quantity of carbon embodied in the fuel.

Much research has focused on carbon taxes. Some scholars compare the effectiveness of CO2 emission controls (Lin and Li 2011; Cosmo and Hyland 2013); some compare carbon taxes with other policy instruments (Gerlagh and Zwaan 2006) and their impacts on both the macro and micro economy (Conefrey, Gerald et al. 2012). In many studies, a carbon tax is analyzed together with a cap-and-trade system because of the carbon restriction inherent in both mechanisms (Johnson 2007; Fischer and Springborn 2011; MacKenzie and Ohndorf 2012; Jenkins 2014). Because of their focus on carbon, the energy- or emission-intensive sectors or enterprises have received greater attention, especially in China (Liang, Fan et al. 2007; Xin Wang 2011; Fang, Tian et al. 2013; Martin, Preux et al. 2014).

In general, both taxes have been found effective to different extents for energy conservation and emissions reduction. The application of these systems in some countries has already shown the cost-effectiveness in CO2 emission reductions of mixed taxes (Lin and Li 2011; Cosmo and Hyland 2013). In the research of Cosmo and Hyland (2013), they note that the implementation of a carbon tax should be considered carefully in terms of the interaction with existing energy taxes, and vice-versa. A practical example is the case of Sweden, where the fuel tax applies to oil, coal, and natural gas. When the emission tax on CO2 was launched in 1991, the overall energy tax burden level was reduced.

The mechanisms of these two taxes are different: a carbon tax reduces CO2 emissions through fuel selection by carbon pricing and works directly on emissions, whereas an energy tax works broadly on influencing fuel prices, encouraging conservation, but has a smaller effect on stimulating fuel switching than on total amount of energy use. Indeed, a carbon tax equalizes the marginal cost of CO2 abatement across fuels, and therefore satisfies the condition for minimizing the global cost of reducing CO2 emissions (Zhang and Baranzini 2004). A carbon tax levied on fossil fuels based on their carbon contents gives clear price signals on carbon cost and covers most CO2 emission sources (Baumol and Oates 1998).

Because of the relationship and difference between the energy and carbon tax, the long- and medium-term effects of the two taxes differ. However, no definitive analysis has yet been conducted regarding how different they are or on their differential effects on various sectors of the economy. Given that China is a developing country and Chinese policy favors economic development, any politically feasible carbon or fuel taxes must balance economic development and its effect on carbon emissions. In this study, we aim to analyze the impacts of two economic instruments, a carbon tax vs. an energy tax, especially their impacts on heavy industries, which are regarded as the backbone of China's economy.

3. Analytical Approach

3.1 Assumptions

There are several ways to levy energy and carbon taxes. In some countries, the coordination of carbon and fuel taxes varies. For example, in the Netherlands the carbon tax was launched without simultaneously changing the country's original tax structure. However, in Finland, Sweden, and Denmark the existing energy tax was reduced when the carbon tax was introduced. In contrast, in Norway the energy tax was increased when the carbon tax was introduced. In China, the existing resources tax and the structure of other taxes imply energy and carbon taxes most similar to those in the Norwegian system.

In this study, we assume a carbon tax will be based on CO2 emissions[1]. Given the current price controls on fuels in China and to simplify the analysis, we assume that the carbon tax will increase the market price of all fossil fuels, and the incremental costs will be fully passed on to downstream industries as direct impacts. This assumption is reasonable because the controlled prices are not completely rigid but adjusted by government authority based on certain rules (see Table 1). The model implementation of the energy tax follows the same assumptions.

Table 1: A Description of the Energy Pricing System in China

Energy type	Pricing	Adjustment bases
Refined oil products	Government guided price	When the moving average price of the international market crude oil for 22 continuous working days changes more than 4%, the domestic price is adjusted based on both processing margins and international crude oil prices.
Natural gas	government guidance price	Based on the 5-year average price of crude oil, LPG and coal, by weights of 40%, 20% and 40%, respectively. The change should not exceed 8% in two adjacent years.
Electricity	Government guidance price	Pricing on regular period：the delivered price is checked annually; if little change between annual costs, the sales price remains unchanged；Linkage pricing: linked with grid power price and is only for industrial and commercial. The adjustment interval should be more than one month.
Crude oil	Market-set price	Based on the changes of supply and demand
Coal	Market-set price	Based on the changes of supply and demand.

Data source: collected and cleared up based on National Development and Reform Commission (NDRC) documents[2]

The original goal of a carbon or energy tax is to promote energy switching and conservation, and therefore the elasticity of energy substitution and demand are important. Substantial differences exist among countries in terms of fuel taxation that, in

---

[1] Considering the method of calculating CO2 emissions by combining the IO table and energy balance, the emissions here are not specifically from combustion or industrial process, but overall totals.

[2] In this study, all the figures and tables without notes on data sources are calculated by the authors.

turn, can lead to large differences in final consumer price (Sterner 2012). As China controls energy prices, its demand price elasticity does not fit the short-term supply and demand relation very well. However, it remains reasonable to assume in long-term that the elasticity can reflect the fuel energy market due to the governmental price control regime. Therefore, following the literature (Johansson and Schipper 1997; Ngan 2010; Xin Wang 2011; Sterner 2012), the overall fuel price elasticity is set as −0.7. As more than 90% of the electricity is generated from fossil fuels [in 2012, the proportion of fossil electricity was 90.2% (NBSNA 2013)], the substitution elasticity between electricity and fossil fuels is higher compared with the substitution elasticity among different fossil fuels.

To make the analysis simple and direct, in this simulation we assume in all scenarios that no significant technical progress occurs in energy use or CO2 emission reduction. Furthermore, no dramatic change occurs in the energy structure, following the targets of the 12th Five-year Plan.

3.2 Models

Substantial challenges exist regarding acquiring energy data in China. For example, sectoral fossil fuels consumption values are not directly available in the Statistical Yearbook of China. In addition, among the 30 categories of energy in the Annual Energy Balance, only seven sectors concern “Input & Output of Transformation” and seven sectors address “Final Consumption.” While the I-O Table has 58 sectors, there are only a few main energy types. Therefore, to obtain emissions data, we have to calculate energy consumption and CO2 emissions in each sector by combining the two tables.

The method we used to calculate energy use and CO2 emissions is as follows:

Total energy use = Total Final Consumption + Transformation in Power Generation and Heating

Total CO2 emissions of a certain type of energy = CO2 emission factor[1] of the energy * amount of energy use

CO2 emission coefficient of a certain type of energy = Total CO2 emissions of the certain type of energy/(Total intermediate use + Total final use − diagonal value of energy sectors)

CO2 emissions of a certain type of energy in a certain sector = CO2 emission coefficient of the certain energy * (Total intermediate use − diagonal value of energy sectors)

Although using the above method we can only calculate each sector’s energy use for 2007, it is reasonable to assume that without dramatic changes in energy structure or energy technology, the energy portfolio of each sector remains approximately the same in subsequent years. In this study, 14 energy types are included in the analysis and their energy uses in different sectors are shown in Appendix 2.

By the above assumptions and data process, we implement a multi-regional general equilibrium model based on the 58 sectors of the 2007 Chinese National IO Tables and combined with economic geography to capture trade between 32 regions (provinces) in China. The original version of this model has been employed in US government agencies to evaluate impacts of various policies (Miller, Wei et al. 2010; Rose, Wei et al. 2011). In this implementation, the production module specifies the production activity in each sector. The production function is Cobb–Douglas, and the inputs in each sector

---

[1] The CO2 emission factors are from 2006 IPCC Guidelines for National Greenhouse Gas Inventories http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_x_An1_Worksheets.pdf

include labor, capital, energy, and other intermediate inputs, following a five-level nested constant elasticity of substitution (CES) function as shown in Figure 1. As energy consumption is sensitive in some sense to capital investment in China, reducing energy consumption is closely related to capital investment types. Therefore, in this model, the energy input changes together with capital inputs, which accompanies substitution for labor. The substitution elasticity in this model is drawn from Ma, Oxley et al. 2009.

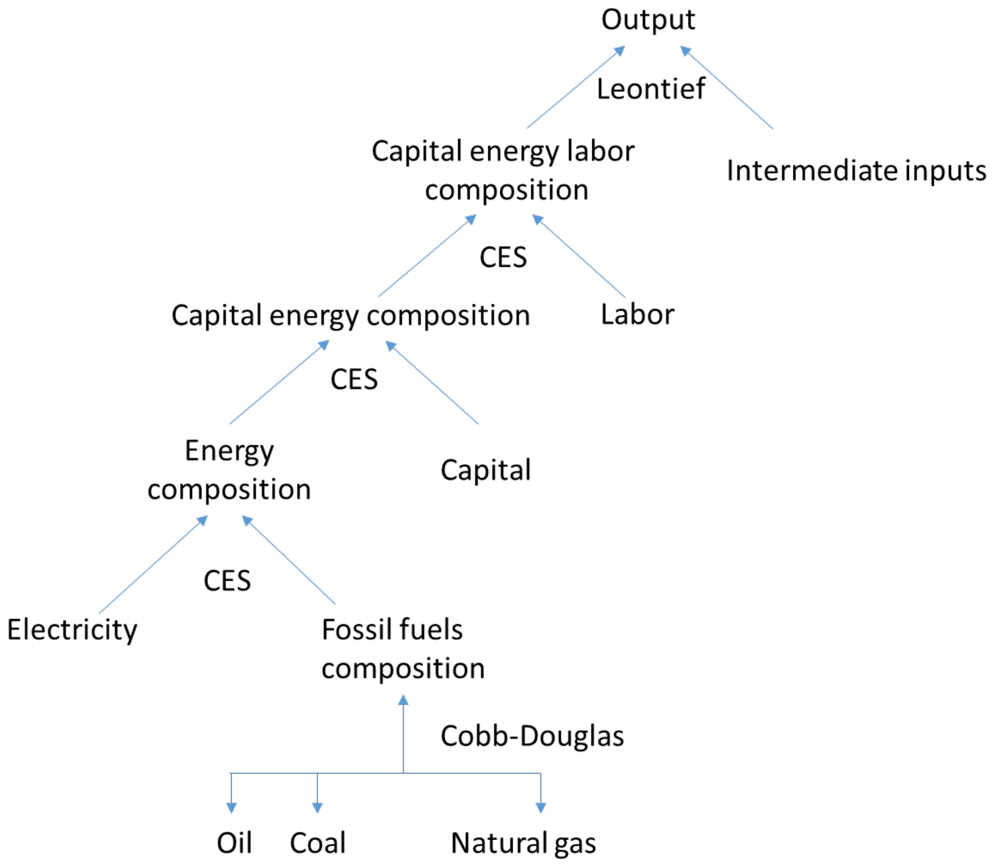


Figure1 Nested production function

For imports, the cost insurance and freight (CIF) value of imported goods is based on the world market price of imported goods plus customs duties and transport costs. Local and imported goods are aggregated through CES functions. Therefore, demand for domestic and imported goods from a given region will be calculated based on the CES function, which minimizes costs. This composite good is used as either intermediate input or final use together with inflow from other regions.

Total exports are calculated using a CES function based on the free on board (FOB) prices and imperfect substitution. World demand for Chinese exports is an exponential function of relative prices. This function has a positive elasticity parameter; this means that when the domestic price of an export good rises, global demand of this certain good will decrease. The import and export structure of the model is shown in Figure 2.

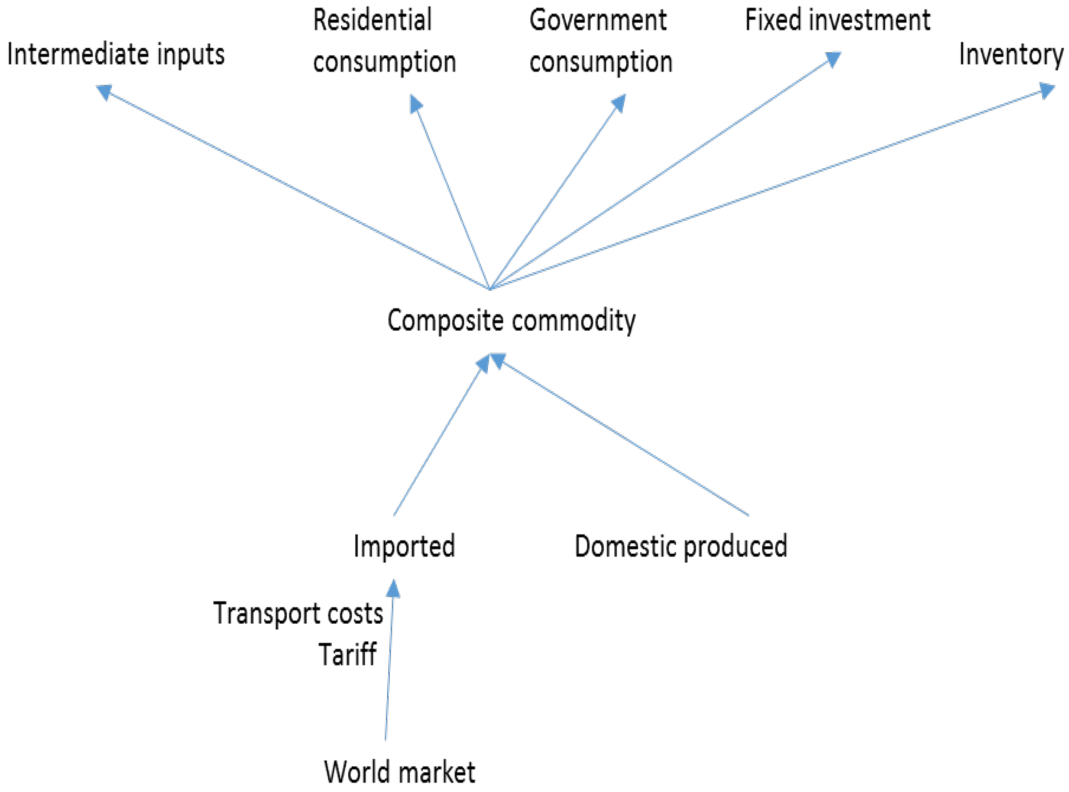


Figure 2 Import and Export Structure

In this study, the marginal rise in costs brought about by taxes is directly reflected in the increase in factor prices, which introduces the tax rate variable into the model. Then in a complete market, for a given output, producers decide the combination of inputs based on minimum costs. The production activity is presented as below:

$$\mathrm{Min.} \sum_{i=1}^{m} P_i(1+t)X_{ij} \tag{1}$$

$$\mathrm{s.t.}\ \ X_j = A_j \sum_{i=1}^{m} X_{ij}^{\alpha_{ij}}, \text{ where} \sum \alpha_{ij} = 1 \tag{2}$$

The Lagrange equation (3) is then differentiated. The demands of sector j for labor, capital, and energy are then determined. In equation (1), $P_i(1+t)$ could be taken as an integrated variable.

$$\mathrm{L} = \sum P_i(1+t)X_{ij} + \lambda[X_j - A_j \sum P_i X_{ij}^{\alpha^{ij}}] \tag{3}$$

$$X_{ij} = [\alpha_{ij} \prod (\frac{\alpha_{ij}}{A_j}) X_j \prod P_i^{\alpha_{ij}} \frac{1+t}{P_i(1+t)}] \tag{4}$$

where X_{ij} is the demand of sector j on factor i; P_i is the corresponding factor price; $\sum_{i=1}^{m} P_i(1+t)X_{ij}$ is the total cost of sector j; α_{ij} is the direct consumption coefficient; X_j is the total output of sector j; and t is the tax rate.

Similarly, the consumption activity function maximizes utility by combining commodities under the budget constraint, as shown in equations (5) and (6):

$$\max \prod_{i=1}^{n} X_{ic}^{\alpha_{jc}}, \text{ where} \sum_{i}^{n} \alpha_{ic} = 1 \tag{5}$$

$$\mathrm{s.t.}\ \ \mathrm{M} = \sum_{i=1}^{n} P_i(1+t)X_{ic} \tag{6}$$

where X_{ic} is the consumer demand for commodity i; α_{ic} is the slope coefficient; and M is the total budget of consumers. Further, the Lagrange equation is expressed as (7):

$$\mathrm{L} = \prod_{i=1}^{n} X_{ic}^{\alpha_{jc}} + \lambda[M - \sum_{i=1}^{n} P_i(1+t)X_{ic}] \qquad (7)$$

After differentiation, the consumer demand of commodity i is as follows:

$$X_{ic} = \alpha_i \frac{M}{P_i(1+t)} \qquad (8)$$

3.3 Data sources and processing

In the standard Chinese IO tables, there are 42 sectors in the various industrial categories. To help analyze the impact of fuel and carbon taxes on different fuels, the standard IO table of 2007 [1] is expanded into 58 sectors by splitting the energy-producing sectors of Mining and Washing of Coal; Petroleum and Natural Gas Extraction; Petroleum Processing, Coking, and Nuclear Fuel Processing; and Electricity and Heat Production and Supply by relying on the 135-sector IO table (as shown in Appendix 3).

As Chinese IO tables are based on a competitive imports assumption that treats imported products the same as domestic varieties, it is necessary to separate emissions embodied in imported and exported goods. Some studies are working on analyzing the emissions embodied in international trade using different methods. A comprehensive one is the study conducted by Koopman et al. (2014). In that study the authors

---

[1] Because the 2010 national IO table is the expanded table based on 2007 IO and there is no 135-sector IO for 2010, in this study we use the 2007 national IO table.

developed a method to extract the value-added from Chinese exports by distinguishing between processing and normal trade. However, because of the complexity required to implement the method in Koopman et al. (2014), this study treats the rest of world as one region, and imported and exported goods are assumed to be of the same quality.

The CO2 emission factors of fuels are calculated based on the intergovernmental panel on climate change (IPCC) guidelines for national greenhouse gas inventories, with conversion to weight-based unit as shown in Table 2.

Table 2 Emission factors of Various Fuels

Emission factor	Unit	Fuel type
2.0483	Ton of CO2/ton energy use	Coal
2.5808	Ton of CO2/ton	Cleaned Coal
0.8193	Ton of CO2/ton	Other Cleaned Coal
3.0651	Ton of CO2/ton	Crude Oil
21.8403	Ton of CO2/10,000 cubic meters	Natural Gas
3.0149	Ton of CO2/ton	Gasoline
3.0967	Ton of CO2/ton	Kerosene
3.1605	Ton of CO2/ton	Diesel Oil
3.2366	Ton of CO2/ton	Fuel Oil
3.1663	Ton of CO2/ton	LPG
3.0651	Ton of CO2/ton	Other Petroleum Products
3.0425	Ton of CO2/ton	Coke
7.4263	Ton of CO2/10,000 cubic meters	Coke Oven Gas
3.2617	Ton of CO2/ton	Other Coking Products

3.4 Scenarios Setting

Energy and carbon tax rates are assumed in the following scenarios. According to some previous studies, China’s carbon tax is expected to be uniform and relatively low to protect competitiveness and economic development (Wang, Yan et al. 2009; Lu, Tong et al. 2010). In this study, we set varied carbon tax in three scenarios: 100, 50, and 10

RMB/ton of CO2 in scenarios A1, A2, and A3, respectively. Energy and carbon tax rates are set based on the consideration that they have comparable effects on the cost increase, which indicates that carbon and energy taxes will take a similar tax payment per unit of fossil fuel, which corresponds to scenario A3 and B. Scenarios C1, C2, and C3 are a compound of carbon and energy taxes.

Additionally, tax revenue recycling has also been discussed in the literature. To enhance the expected effects of tax instruments on emission reduction as well as to mitigate the unevenness of income reallocation (Chamon, Liu et al. 2013; Du, Liu et al. 2014), revenue is recycled by reducing indirect taxes and giving a price subsidy to households.

Noting that most current energy tax proposals only focus on adding a tax on the primary energy (Han, Su et al. 2008; Liu and Sun 2014), we set the scenarios of energy tax as “only implemented on primary energy of oil, coal, and natural gas” to more closely approximate reality and avoid distraction.

Table 3 Simulation Scenarios

Scenario	**Description**
A1	Carbon tax: 100 RMB emission
A2	Carbon tax: 50 RMB/ per ton CO2 emission
A3	Carbon tax: 10 RMB/ per ton CO2 emission
B	Fuel tax: 5% of the delivered price for oil, coal, natural gas
C1	A1+B
C2	A2+B
C3	A3+B

4. Simulation Results

4.1 General Economic Impacts

In all five scenarios, we simulate the impacts of different tax combinations on

Chinese macroeconomic indicators and industrial structure. These taxes have the greatest effect on production costs and the prices of certain products and commodities. Table 4 shows changes in GDP, real disposable personal income, and the price index.

The results indicate that imposing a carbon or energy tax will have negative impacts on all indicators. But the magnitudes of the impacts differ. Basically, as described in equations (1)–(8), the energy tax will first shock the delivered prices of crude oil, raw coal, and natural gas; further, the impacts are passed downstream through production costs of all commodities before finally affecting household consumption. In contrast, the carbon tax is levied directly on emitters, covering all manufacturing industries and imposing costs according to their emission intensities. Because of the different functioning of the two mechanisms, from Table 4 it can be observed that the effect on GDP in carbon tax-only scenarios (A1–A3) is larger than those observed in fuel tax scenario (C1–C3). In contrast, real disposable personal income in scenarios C1–C3 is more adversely affected than in scenarios A1–A3.

Additionally, both the carbon and energy are somehow “shrinking taxes,” whose total revenues are shrinking along with reductions in total emissions or fossil energy use. In carbon energy taxes issues, along with the efforts of reducing total CO2 emissions or the amount of fossil energy use, the proportion of taxes out of production costs is shrinking. In Table 4, the negative impacts on GDP and real disposable income both diminish over time despite fluctuations in the beginning phase.

By comparing scenarios A1–A3 with C1–C3, we find that the impacts of the combined carbon-energy tax mix are not equal to the effects of a single carbon tax and a single energy tax. In year 2015, the impacts of A1 and C1 on GDP are both −0.381%. Additionally, in most of the time points (2020–2040) the impacts of C1 (A1 + B) on

GDP are quite similar to those of A1. However, in the final years (2035–2040) the impacts of C1 become smaller than those in A1. This could reflect the fact that both the carbon and fuel taxes work on fossil energy consumption and related emissions, so that when these two taxes are implemented simultaneously, the subject of the carbon tax is no longer producing the same emission amounts as without the fuel tax, and vice versa. In other words, these two taxes "weaken" each other. In terms of real disposable personal income, the effects in the A scenarios are bigger than those in the C scenarios, as shown in Table 4. Because the carbon tax impacts the general price (PCE-price index) less than energy tax, real disposable personal incomes in A scenarios are affected less than those in C scenarios.

Table 4 Impacts on GDP and Real Disposable Income

	2015	2020	2025	2030	2035	2040
GDP						
A1	-0.381%	-0.762%	-0.581%	-0.496%	-0.480%	-0.458%
A2	-0.194%	-0.392%	-0.293%	-0.250%	-0.243%	-0.232%
A3	-0.039%	-0.080%	-0.059%	-0.050%	-0.049%	-0.047%
B	-0.193%	-0.351%	-0.285%	-0.265%	-0.276%	-0.286%
C3	-0.039%	-0.080%	-0.059%	-0.050%	-0.049%	-0.047%
C2	-0.193%	-0.390%	-0.294%	-0.249%	-0.241%	-0.230%
C1	-0.381%	-0.758%	-0.582%	-0.496%	-0.476%	-0.454%
Real Disposable Personal Income						
A1	-0.391%	-0.658%	-0.514%	-0.458%	-0.467%	-0.464%
A2	-0.199%	-0.340%	-0.259%	-0.230%	-0.236%	-0.235%
A3	-0.040%	-0.070%	-0.052%	-0.046%	-0.048%	-0.047%
B	-0.271%	-0.378%	-0.319%	-0.302%	-0.317%	-0.331%
C3	-0.041%	-0.070%	-0.053%	-0.047%	-0.048%	-0.048%
C2	-0.202%	-0.343%	-0.264%	-0.234%	-0.237%	-0.235%
C1	-0.397%	-0.665%	-0.524%	-0.466%	-0.469%	-0.465%

Sectoral investment is affected directly in all scenarios, due to the rise in marginal production costs. Compared with consumption expenditure, the percentage decrease of investment is almost twice as much before 2025. Although lower after 2025, it remains more than 1.5 times the decline in consumption expenditure until 2040. An exception is scenario B, where the percentage drop in investment is between 1.2 to 1.9 times over consumption. This result indicates that the energy tax, as a broader based tax as mentioned above, affects not only manufacturing sectors, but also household consumption and commercial sectors through the price transmission of fuel products. This is particularly true when considering that a relatively large proportion of petroleum products are used by residential vehicles and related transportation (see figures 3 and 4 below).

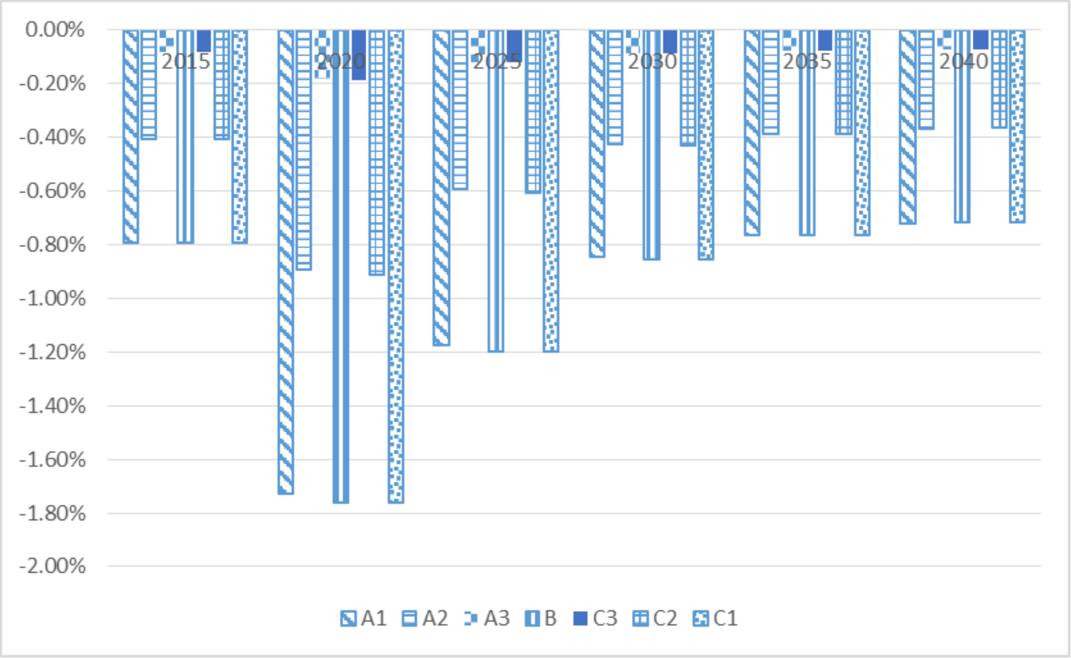


Figure 3 Change in Gross Private Domestic Fixed Investment

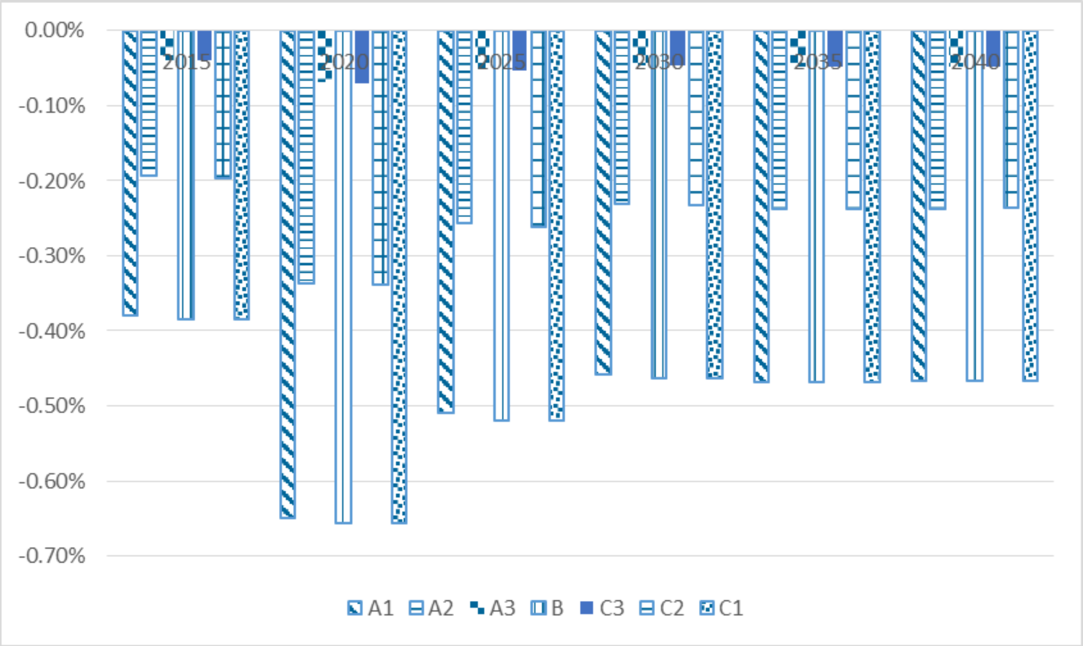


Figure 4 Change in Personal Consumption Expenditures

4.2 Impacts on CO2 emissions and energy use

Both the fuel and carbon taxes reduce CO2 emission and encourage energy conservation. Total amounts of energy use and CO2 emissions as well as their intensities both decrease.

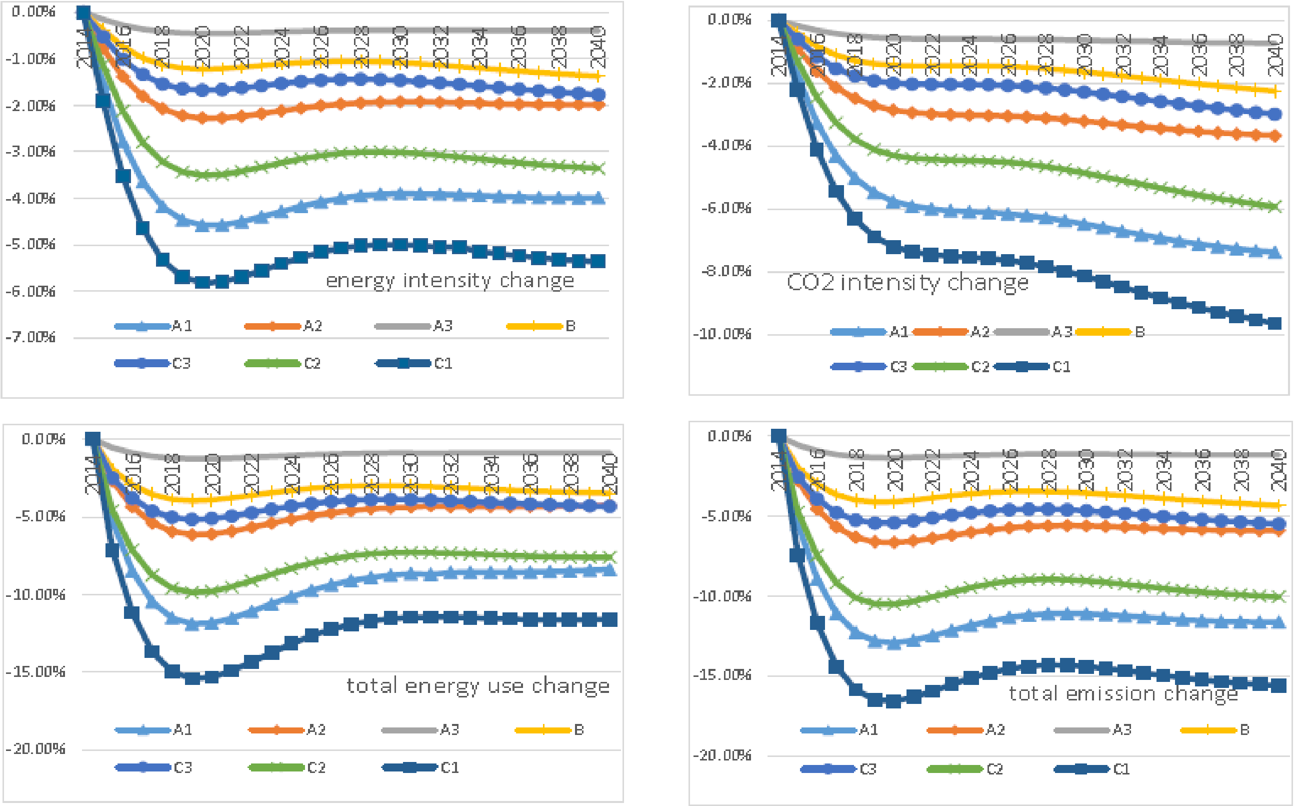


Figure 5 Changes in total energy use, energy intensity, total emissions, and emission intensity in all scenarios

Figure 5 shows that the total amounts of energy use and CO2 emissions as well as their intensities decrease. There appears to be a U-curve (some overshooting) in the changes of energy intensity, total energy use, and total emissions. Because we assume no dramatic change occurs in technologies, changes are determined by sectoral outputs. The changes can be characterized as occurring in three phases: 2014–2020 rapid decrease; 2020–2025 rebound; and 2025–2040 stable phase. In the rapid decrease phase, the effects of carbon and energy taxes are most significant. Although GDP is affected in this phase, energy consumption and related emissions decrease more quickly. The changes mainly stem from the effect of taxes on investment. In this model, total investment comprises three parts: residential, non-residential, and capital equipment. In addition, commercial inventory is also a part of investment, determined by current average price and based on the national change in inventories as a proportion of sales applied to the size of local industries (Richman, Shao et al. 1993). Residential and non-residential investment stocks are shown as below in Table 5.

Table 5 Changes in Regional Residential and Non-residential Capital Stock across Scenarios

Scenario	2015	2020	2025	2030	2035	2040
A1						
Residential Capital Stock	-0.036%	-0.402%	-0.540%	-0.509%	-0.483%	-0.477%
Nonresidential Capital Stock	-0.055%	-0.584%	-0.872%	-0.904%	-0.872%	-0.836%
A2						
Residential Capital Stock	-0.019%	-0.208%	-0.277%	-0.258%	-0.244%	-0.241%
Nonresidential Capital Stock	-0.028%	-0.301%	-0.447%	-0.460%	-0.442%	-0.424%
A3						
Residential Capital Stock	-0.004%	-0.043%	-0.056%	-0.052%	-0.049%	-0.049%
Nonresidential Capital Stock	-0.006%	-0.062%	-0.091%	-0.093%	-0.090%	-0.086%
B						
Residential Capital Stock	-0.021%	-0.190%	-0.249%	-0.241%	-0.238%	-0.244%
Nonresidential Capital Stock	-0.019%	-0.195%	-0.293%	-0.314%	-0.324%	-0.337%
C3						
Residential Capital Stock	-0.004%	-0.043%	-0.057%	-0.053%	-0.050%	-0.049%
Nonresidential Capital Stock	-0.006%	-0.061%	-0.091%	-0.094%	-0.090%	-0.086%
C2						
Residential Capital Stock	-0.018%	-0.208%	-0.279%	-0.262%	-0.247%	-0.242%
Nonresidential Capital Stock	-0.027%	-0.296%	-0.445%	-0.461%	-0.444%	-0.425%
C1						
Residential Capital Stock	-0.036%	-0.402%	-0.545%	-0.517%	-0.489%	-0.479%
Nonresidential Capital Stock	-0.053%	-0.573%	-0.868%	-0.907%	-0.875%	-0.838%

In fact, nonresidential capital stock is a more significant driving force for energy use reduction than residential capital stock. When the energy or carbon tax is first implemented, sectors would reduce new investments due to the rise in marginal production costs. Without adequate time to switch to new manufacturing technologies or energy alternative technology, new project investment mainly comprise relatively advanced technology. Over time, manufacturing sectors turn to energy-saving technology, low-carbon technology, or low-carbon energy; corresponding new investment gradually increases, which is relieved from the lock-in effects of the high-energy technology. When this new round of energy-saving investment is finished because of the relatively stable cycle of technology progress, no other more-advanced technology exists to replace it (notice that in this study, it is assumed that no dramatic change occurs in technology or energy). This slows the incremental accumulation of real capital stock.

4.3 Impacts on High Energy-Consuming Industries

According to a definition issued by National Development and Reform Commission (NDRC), the “high energy-consuming industries” are the non-metallic mineral products industry; chemical raw materials and chemical products industry; metal smelting and rolling processing industry; electricity and heat production and supply; and the petroleum processing, coking, and nuclear fuel processing industry (NBS 2011). These high energy-consuming industries are anticipated to be affected most by the carbon and energy taxes. In contrast, these industries are also the mainstay industries in China. In 2013, the value-added of these industries increased 10.1% on average since 2012, ranking fourth after automobile manufacturing (14.9%); computer, communications and other electronic equipment manufacturing (11.3%); and electrical machinery and equipment manufacturing (10.9%). Therefore, evaluating the impact of carbon and energy taxes on these industries is important. In general, the energy tax and carbon tax both effectively reduce energy use in these industries.

Figure 6 shows that the impact of the carbon and energy taxes differs by sector. Generally, employment in all sectors shrinks in the short run and recovers in the long run. In all carbon tax scenarios (A1–A3, C1–C3), the electricity and heat supply industry experiences the most modest employment impact while the policy is in effect. The non-metallic mineral products manufacturing industry bears the heaviest impact in 2020 (−14.86% and −15.09% in A1 and C1, respectively), but recovers after 2020 to be third most heavily affected sector with employment losses of 7.36% in both A1 and C1. In contrast, the effect of the carbon tax on the petroleum processing, coking, and nuclear fuel processing industry grows relatively larger in 2030 and 2040 compared with other industries, changing from the third largest in 2020 to the largest in 2040. In the scenario without a carbon tax (scenario B), the situation differs. Petroleum processing, coking, and nuclear fuel processing industries and the metal manufacturing and processing industry are the most affected in 2030 and 2040, and by 2030, the petroleum processing, coking, and nuclear fuel processing industry exceed the metal manufacturing and processing industry to become adversely affected. Another difference between the fuel and carbon taxes is that the impact in scenario B does not decrease along with time, unlike those in scenarios A and C. On the contrary, employment in 2040 in scenario B is lower than in 2030.

From the perspective of change extent, according to the impact on the whole economy, the fuel tax “offsets” the impacts of the carbon tax, which means the impact of C1 is very close to that of A1, but not to that of A1 + B. Figure 6 Impacts of carbon energy taxes on Employment in A1, B, and C1. Additionally, the output of these sectors follows same impacts from the carbon energy taxes, but the magnitude of change in output between industries is smaller than that seen for employment. Across all industries, Petroleum Processing, Coking, and Nuclear Fuel Processing see the greatest decline in output; almost all petroleum products such as diesel, gasoline, fuel oil, LPG, and others as well as coke products are included in this sector. In this broad industry, fuel oil is the most severely affected, bearing an output loss of 24.68% in 2020 and 26.73% in 2030, which is also the biggest loss across all industries. Nonmetallic Manufacturing and Processing bears a loss of 15.88% and 10.83% in these two years and ranks fourth out of all industries. Among the heavy industries, LPG displays the smallest amount of decrease in output in 2020, 7.06% less than the reference scenario, even less than professional and technical services industry, whose output declines by 7.29%.

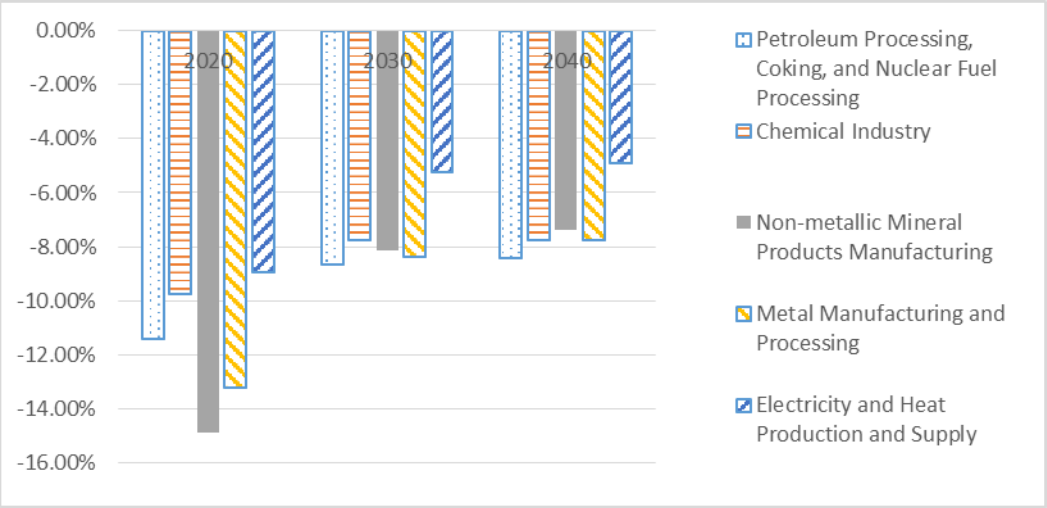


Figure 6-a Employment impacts of A1

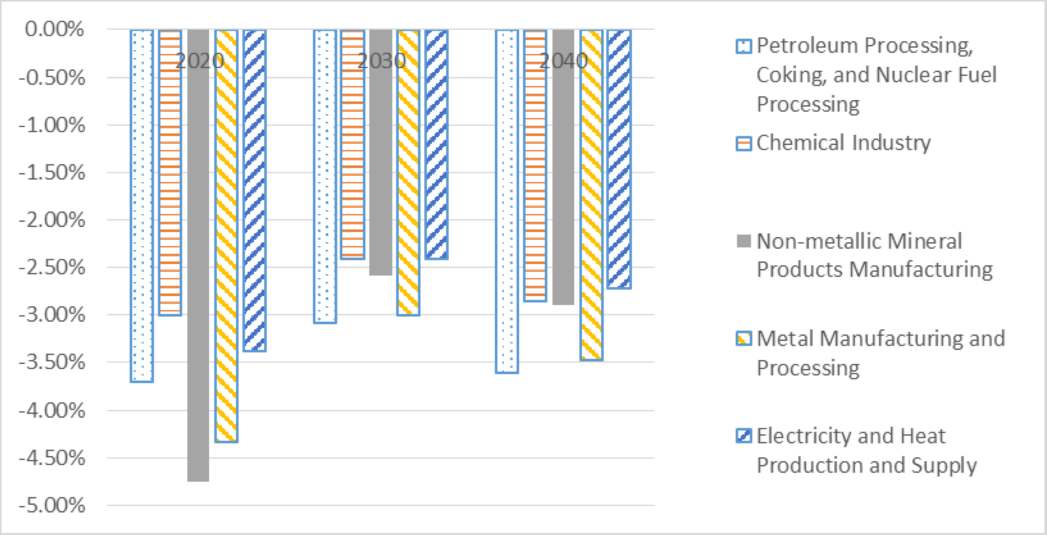


Figure 6-b Employment impacts of B

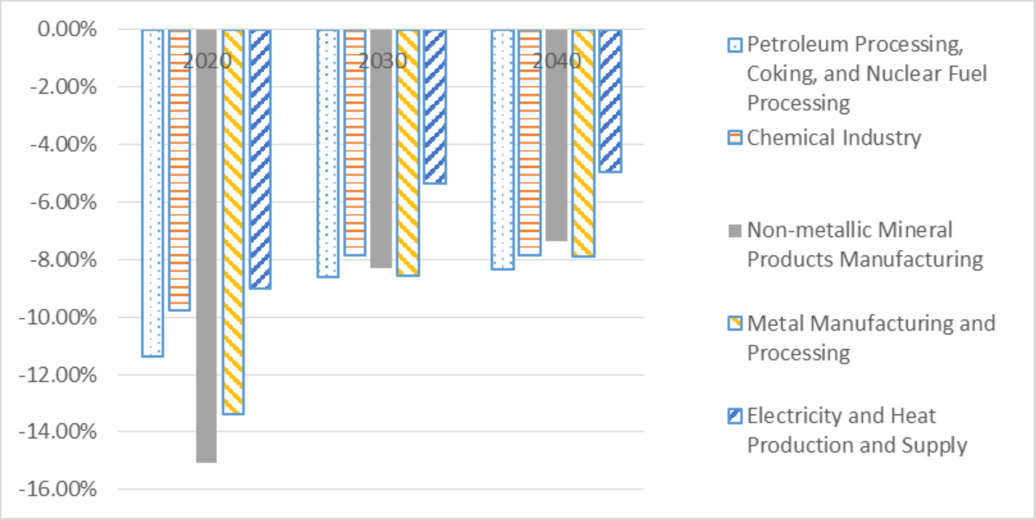


Figure 6-c Employment impacts of C1

The impact on energy use varies across different scenarios. Consistent with employment and output effects, the Nonmetallic Mineral Products Manufacturing sector experiences the greatest decline in energy use of any industry in 2020, falling by 20.12% (C1). The decrease of energy use in petroleum processing, coking, and nuclear fuel processing and metal manufacturing and processing industries rebound slower than other industries in the long term after 2020. Unlike with employment and output, the decrease in energy use involved in the carbon-energy combined tax is significantly greater than in carbon tax-only scenarios. In energy tax scenario (B), the energy use of the electricity and heat industry decreases more than the chemical industry; whereas, in carbon tax scenarios (As and Cs), the energy use of chemical industry decreases more than that of the electricity industry after 2020.

All these selected heavy industries contribute large energy savings to the whole economy. Their decreased proportions of energy use range from 32.3% to 94.5% compared with the baseline, which are much larger than the average reductions for all other sectors. Complete results are shown in Appendix 4.

4.4 Impacts of the Two Taxes on Imports and Exports of High-Energy-Consuming Industries

Carbon and energy taxes have different impacts on the total imports and exports as well as different sectors' imports and exports.

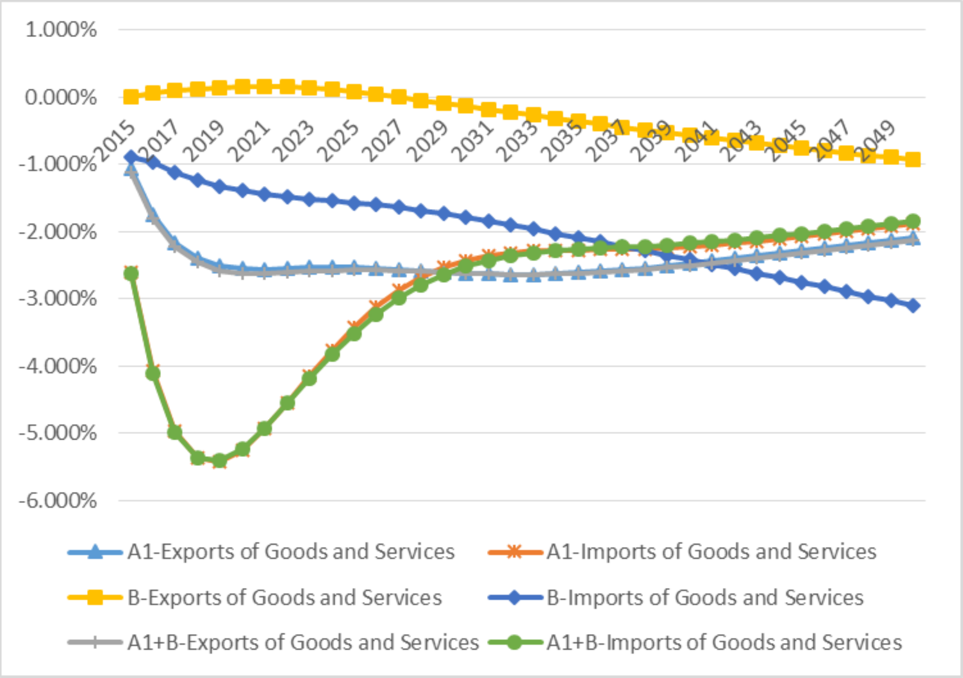
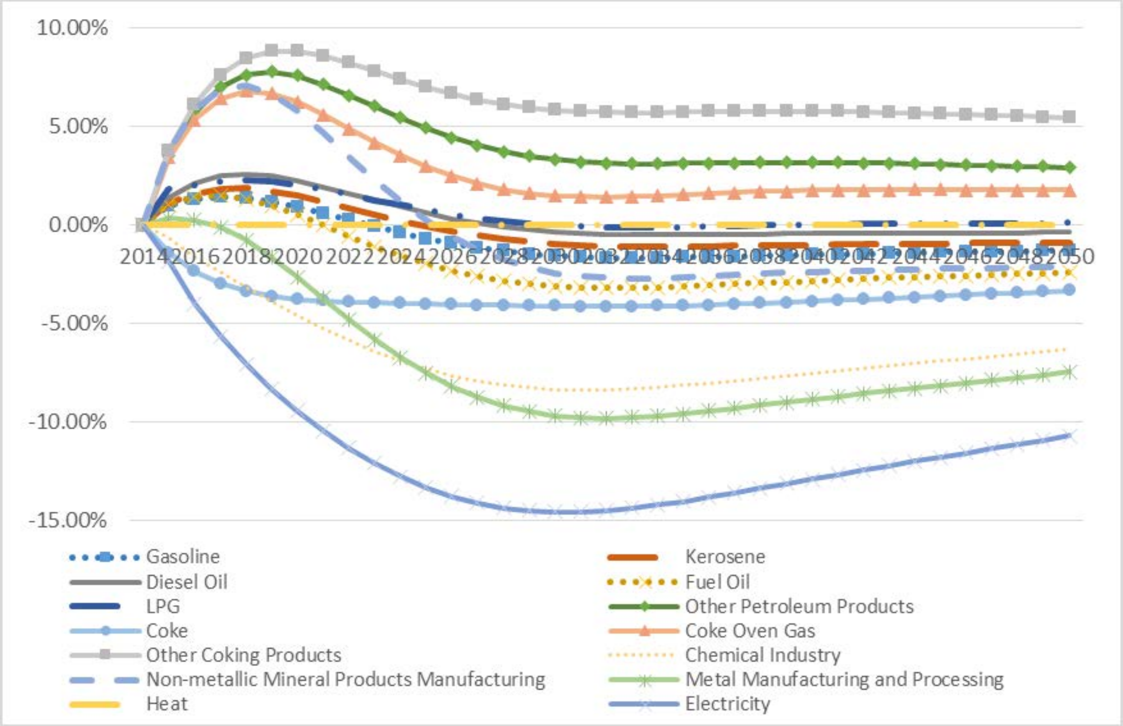


Figure 7 Export and import change in A1, B, C1 (A1+B) compared to baseline scenario

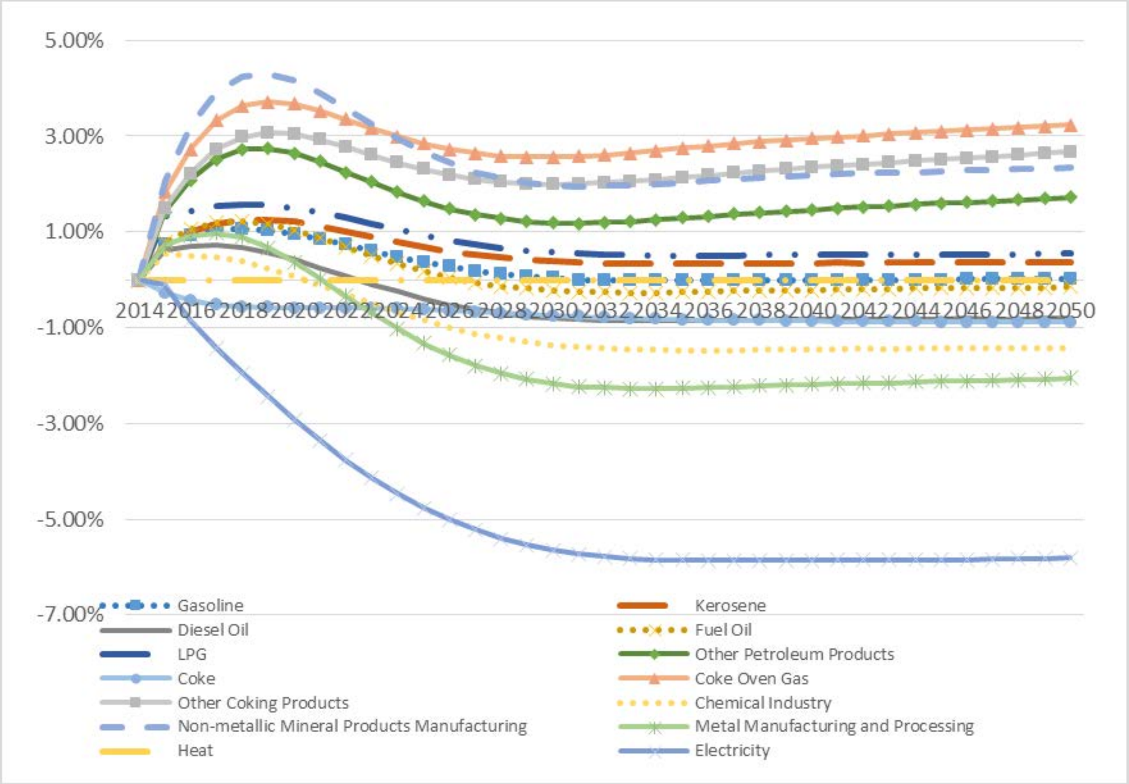
In these scenarios, the impacts of the energy and carbon taxes on exports are relatively steady with decreases of −2% to −3.5% relative to the baseline scenario (Figure 7-a)). However, their impacts on import are more significant. In scenarios with a carbon tax (A1 and A1 + B), after a short time of the tax being implemented, imports drop significantly, close to −6% in 2019, followed by a slower increase. However, the impact on imports from an energy tax only (B) is relatively much smaller. As the carbon tax targets all emissions, including those in sectors that do not consume much energy directly but still have CO2 emissions such as the chemical industry and transportation industry, the whole economy is affected by the increased costs facing most sectors. Therefore, production in all these sectors is affected, including those sectors that rely principally on imported intermediate inputs. In contrast, the energy tax is more focused on the sectors directly using energy in production with predominantly domestic production chains, with imports and exports affected in same trends (Figure 7-a).

To further examine the differential impact of the taxes on the selected heavy industries, we decompose the petroleum processing, coking, and nuclear fuel processing industry into sub-industries. In carbon tax scenarios (A1), because the extent of the decrease in import is bigger than that of export, net exports of most energy intensive sectors tend to increase in the first 3–5 years then decrease in the next 10–15 years before becoming stable as a lower-than-baseline scenario. But the net exports of the electricity, chemical industry, and coke sectors decrease from the very beginning of the policy. Furthermore, the net exports of coke oven gas, other coke products, and other petroleum products sectors increase much more than those of other sectors and become stable at a higher level than in the baseline scenario. However, due to the different scale of sectoral effects, in scenario B, the chemical industry goes through a similar process as most of the other energy intensive industries. Net exports of the chemical industry increase by 0.54% in 2015 and then start decreasing in 2020, but do not decrease at the very beginning as in scenarios A1 and C1. Though the chemical sector's exports are determined by its domestic prices, when taxes are first implemented, the price of chemical products increases quickly, dramatically shrinking domestic demand. Meanwhile, because of the lock-in effect of production technology, the producers cannot reduce production quickly in the short term. In contrast, a large part of the chemical sector's production is used as intermediate inputs in other sectors, whose production levels will also decrease because of the rise in marginal costs. Demand for chemicals by other sectors therefore declines. Although total exports and imports both decrease, in the short-run, the decline in imports is larger than in exports, yielding a small increase in net export. In the long run, because demand for Chinese exports on the world market is an exponential function of relative prices, total exports of the chemical sector still decrease even after prices have adjusted.

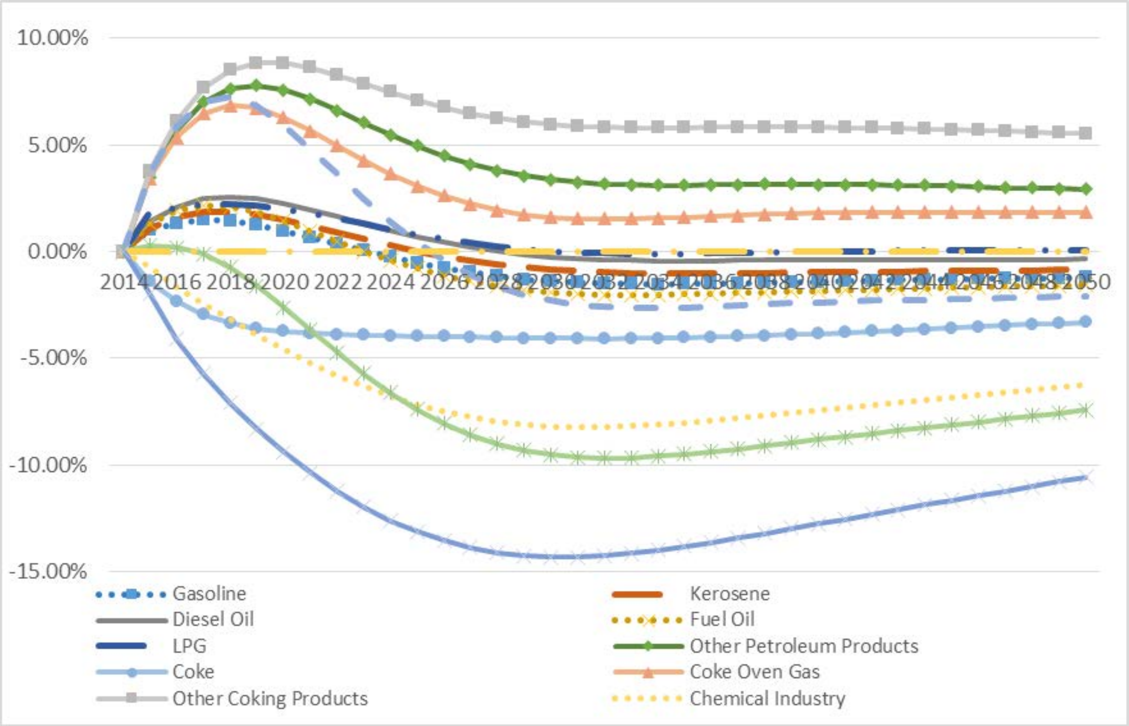
As mentioned above, electricity generation, the chemical industry, and the coke industries all demand large amounts of energy as inputs or intermediate inputs but are not direct consumers. The impacts of a carbon tax on these sectors' net exports are more significant; meanwhile, in the carbon tax scenarios, net exports apparently rebound from 2030 to 2032—an outcome not seen in energy tax scenarios.



8-a Changes of net exports of energy intensive industries in scenario A1



8-b Changes of net exports of energy intensive industries in scenario B



8-c Changes of net exports of energy intensive industries in scenario C1

Figure 8 Changes of net exports of energy intensive industries

4.5 Impacts on the Competitiveness of Energy-Intensive Industries

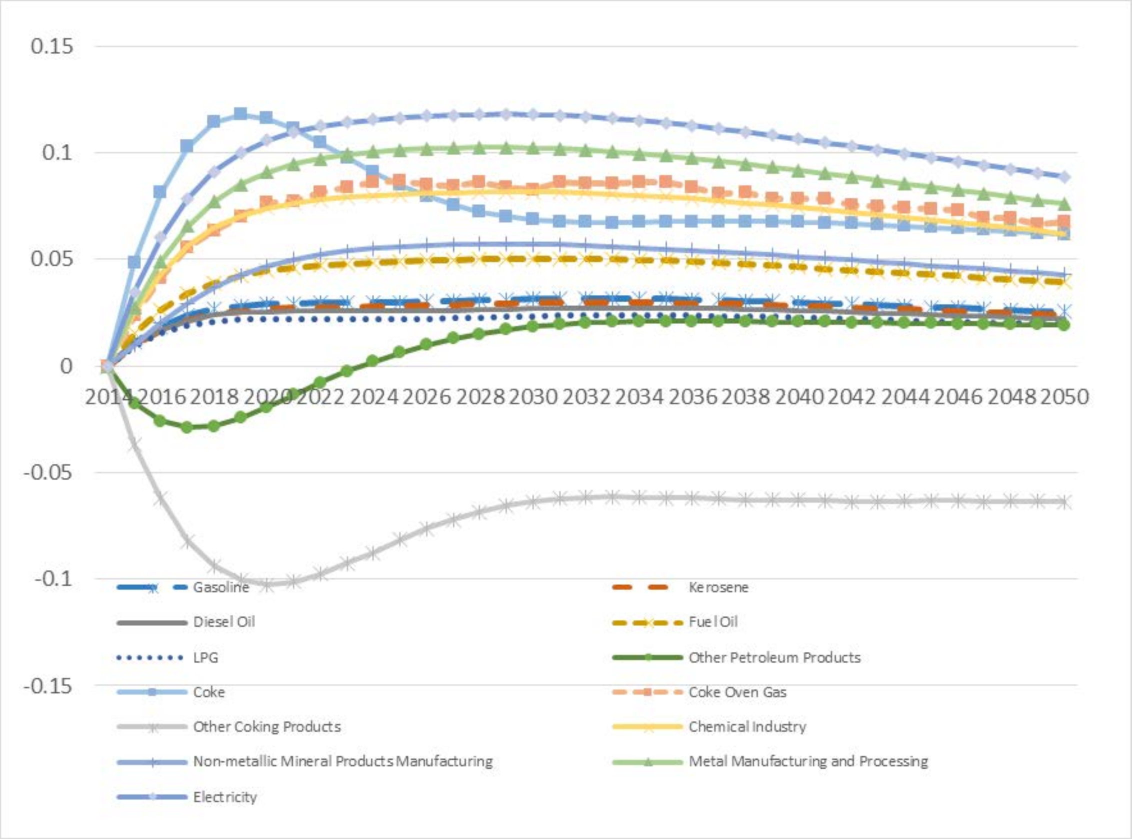
A major driver of China’s rapid economic growth is thought to be the supporting role of heavy industrial goods in total exports. The cost of this “high export and high growth” strategy has been a subject of debate, with increasing number of researches pointing out that it is a transfer emission issue because these heavy industries export finished goods abroad while domestically emitting pollutants and greenhouse gases due to their relatively low production costs (Douglas and Nishioka 2012; Guo, Zhang et al. 2012; Ren, Yuan et al. 2014). Therefore, it is reasonable to worry that taxing these heavy industries would harm their competitiveness not only internationally but even domestically. It is therefore necessary to analyze the competitiveness of these industries considering the associated environmental costs, which can be accounted for by a carbon tax.

Definitions of “sectoral competitiveness” differ across researches, and most tax-related studies measure competitiveness by the share of domestic product exported to international markets (Baek, Jung et al. 2014; Meleo 2014; Wang and Wang 2014; Zhang 2014). However, in this study we are concerned more with the domestic market and want to reflect the impact of taxation on competition between domestic and imported goods. We therefore define the “domestic competitiveness” of a given sector as

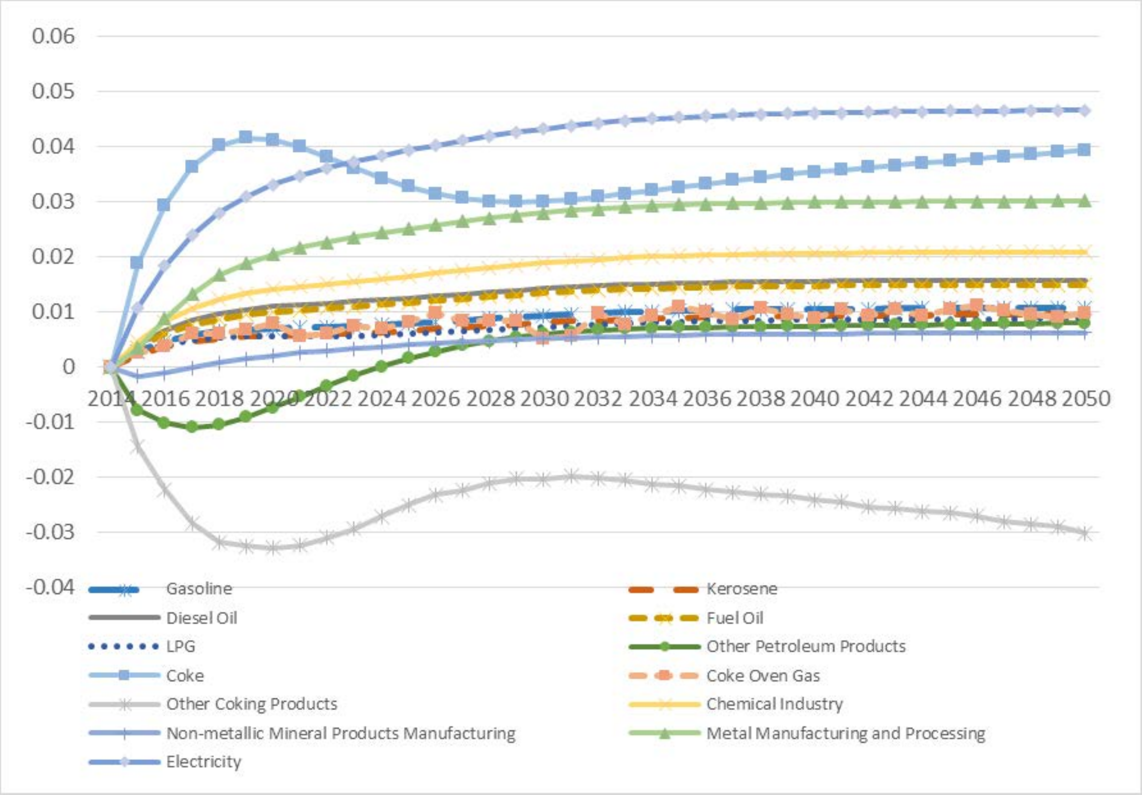
$$CMP_i = \frac{NE_i}{D_i} = \frac{E_i - M_i}{Y_i - E_i + M_i} \qquad (9)$$

For a certain industry i, CMP_i is the domestic competitiveness, NE_i is net exports, D_i is the total domestic demand for industry i, E_i is net exports, M_i is imports, and Y_i is the total output of industry i.

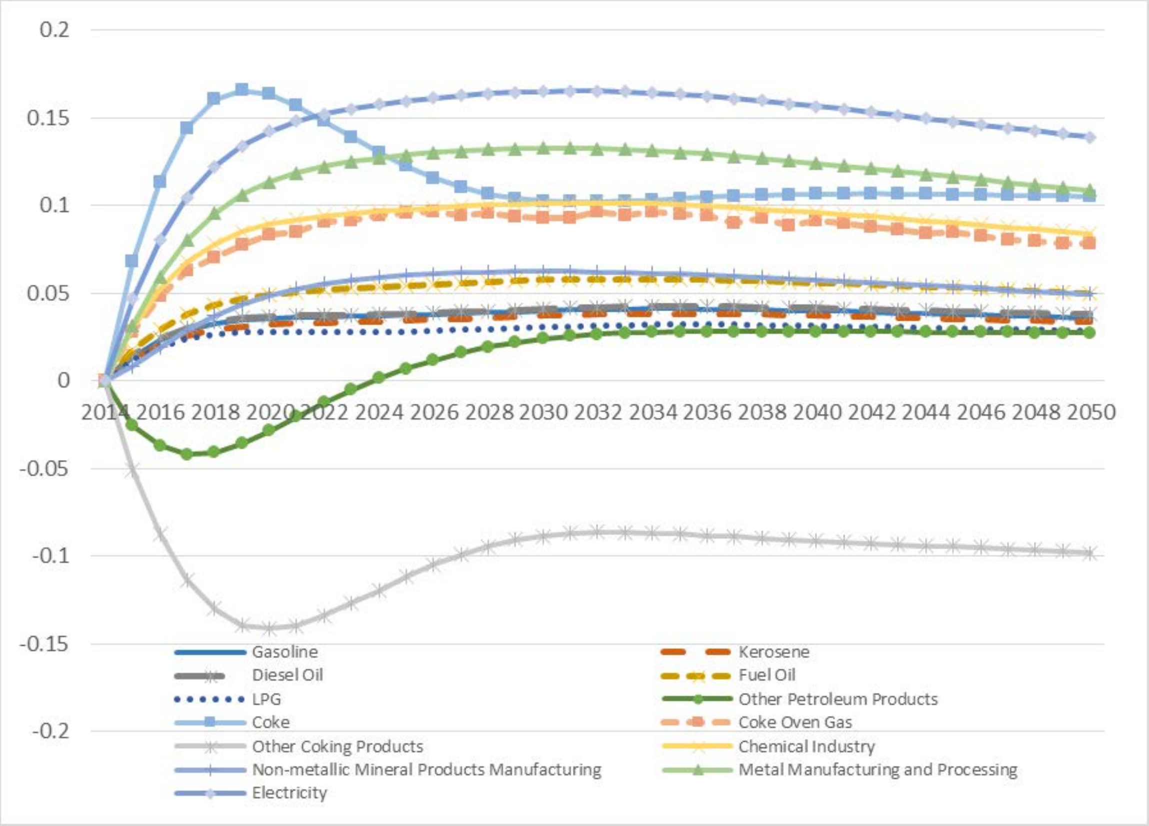
The proportion of imports in a sector indicates, to some extent, a sector’s openness and dependency on foreign products, which together reflect the domestic competitiveness of a given sector. In contrast, the proportion of exports of a given sector out of total output reflects the relative importance of domestic and international markets. The higher the rate, the higher the sectoral export dependency. Therefore, when we examine the CMP in a given scenario, we could find that although the CMPs of other coking products and other petroleum products are lower than those in the reference scenario, all other heavy industries are more dependent on exports, which verifies the common perception of expansion of heavy industry exports as the main driving force of China’s relatively high economic growth. Considering coking products and other petroleum products are a small part of the whole economy, it is reasonable to conclude that carbon and energy taxes both increase heavy industries' dependence on exports. The energy tax goes further and amplifies the effects of the carbon tax in scenarios C1–C3.



9-a Difference of CMP in A1 compare to baseline



9-b Difference of CMP in B compared to baseline



9-c Difference of CMP in C1 compared to baseline

Figure 9 Changes of CMP in A1, B and C1 compare to baseline

4.6 Comparison of costs and efficiency of energy tax and carbon tax

In this section, we try to discuss two questions: which tax reduces CO2 emissions more when they have the same total revenues (higher efficiency)? And, whose economic impact is larger when they reduce CO2 emissions by the same amount (lower cost)?

We take the 5% energy tax as a benchmark to analyze which policy is more effective in emission reduction while holding tax revenue constant. When the carbon tax is set at 11.87 RMB/ton of CO2, in 2020 the total revenue is the same as for a 5% energy tax, i.e., 92.66 billion RMB. The economic effects, however, differ. Compared with the effects of the carbon tax, the energy tax leads to a greater initial decrease in both energy and emission intensity followed by continued decline and higher velocity emission intensity, as shown in Figure 10.

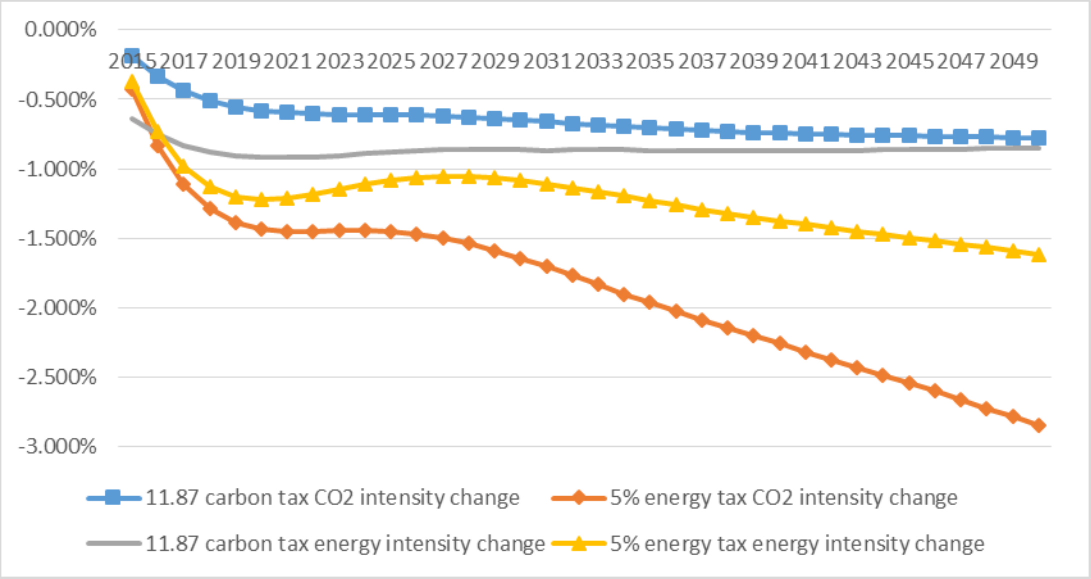


Figure 10 Emission intensity and energy intensity of 11.87 RMB carbon tax and 5%-of-price energy tax

Total emission reductions also differ. In the initial period, the carbon tax has significant effects of reducing CO2 by 408.17 million tons, while the energy tax induces reductions of 297.13 million tons of CO2, and this same relationship persists until 2021. Over time, the total reduction induced by the carbon tax abates, whereas that by the energy tax continues growing. By 2040, the total emission reduction from a 11.87 RMB carbon tax is 69.63 million tons of CO2, while that of 5% energy tax reaches 443.6 million tons of CO2, over six times as great.

Additionally, the impact on the broader economy also differs. In 2020, although the total revenue of the energy and carbon taxes are same and are both recycled to households, the GDP in the energy tax scenario drops 0.74% more than the baseline, while that of the carbon tax scenario drops only 0.37%, i.e., half as much. However, the gap is not as significant for real disposable income: the 11.87 RMB carbon tax reduces real disposable income by 0.325%, while the 5% energy tax results in a decrease of 0.378%. The difference in economic effects mainly comes from investments, including sectoral fixed investment and inventory, plus sectoral imports and exports. Because the carbon tax does not work directly on energy use but on all emissions, this mechanism offers more choices to the manufacturing industries regarding emission reduction measures, allowing the economy to recover and adjust through market mechanisms. In all carbon tax scenarios, GDP losses shrink annually. In 2030 and 2040, the loss compared to baseline is 0.230% and 0.215%, respectively. On the contrary, the energy tax is less flexible, resulting in GDP losses of 0.265% and 0.286% in 2030 and 2040, respectively.

For the sake of symmetry, we analyze the economic impacts of these two taxes while holding emission reductions constant. Still taking the effect of a 5%-of-price energy tax in 2020 as reference, we find that a carbon tax of 10.3 RMB/ton achieves the same level of emissions reduction. In 2020, both of these instruments reduce CO2 by 369.64 million tons. The GDP loss with a 10.3 RMB carbon tax is 0.063% in 2020, gradually falling to 0.047% (2025), 0.040% (2030), 0.039% (2035), and 0.037% (2040), which are around 20% of GDP loss from the reference 5% energy tax (scenario B) in Table 1. Real disposable incomes also follow the same trend.

From the two comparison exercises above, we can conclude that an energy tax will have different effects than a carbon tax, namely they have different functions in terms of reducing energy use and carbon emissions. In a policy simulation, if we set emission reduction as the priority, the energy tax will act faster and more efficiently than the carbon tax, albeit with greater economic costs. In the long run, however, the energy tax will reduce energy intensity and CO2 emission intensity significantly, while the carbon tax sees a rebound in both energy intensity and CO2 emission intensity after an initial period of decline.

Some variant of the simulation scenarios laid out above is anticipated to be introduced in China in 2015. If for some reason, a tax policy was not implemented by that time, what would be the consequences of a delay? We first assume that the taxation policy starts one year later (2016). Under the 10 RMB scenario, in 2030, the fall in emission is 8.17% less than in scenario A3, which is projected as starting in 2015. If the taxation policy starts five years later (2020), then at the same tax rate of 10 RMB, emission decreases by 36.7% less than in scenario A3 in 2030. If the carbon tax starts from 2020 with a target of the same reduction amount in 2030 as in scenario A3, the 2020 tax rate should be 18.4 RMB, leading to a decline in GDP in 2030 i.e., 3.56% greater than that in scenario A3. In contrast, postponing the introduction of the tax will keep the economy growing in the same speed as the baseline, requiring a much higher tax to achieve the same emissions reduction as in scenario A3. Under this target, the tax rate rises to 23.57 RMB/ton of CO2 emissions.

Similarly, when implementation of the energy tax is postponed to 2020, the tax rate should be set at 11.78% of the energy price to reach the same reduction amount of CO2 emissions as in scenario B in 2030, and the GDP loss will be 5.71% more than that in scenario B. A tax rate of 17.21% of the energy price is required to achieve the same emission intensity in 2030 as that of scenario B, reducing GDP by 8.20%. Obviously these losses and costs are not acceptable.

5. Conclusions

In this study, we analyzed the function of a carbon tax, an energy tax, and their combined impacts on the whole economy and on industrial performance. Our principal conclusions are as follows.

In the long run, both an energy tax and a carbon tax help sectors to reduce energy use and corresponding CO2 emissions; in the short run, production costs will rise followed by a slight loss of GDP. In all scenarios, along with the increase in tax rates, a relatively modest decline in GDP will occur. In scenario A1, which shows the greatest policy response, GDP declines to 0.762%, the greatest loss across all scenarios. Although GDP losses are not the biggest, in the energy tax-only scenario (B), the impacts on total investment and total consumption are the largest. In 2020, the impact of scenario B on GDP is −0.272%, the second smallest after the rate observed in scenarios A3 and C3. However, its impacts on total investment and total residential consumption are −1.76% and −0.66%, respectively, the greatest of all scenarios. This means that compared with a carbon tax, the energy tax functions better with respect to sectoral investments for new projects or retrofits to existing projects. In other words, the energy tax is more effective at reducing production and consumption of energy-intensive products through the path of restricting investments in energy-intensive sectors.

Compared with the energy tax, the carbon tax has more obvious effects on reducing energy consumption and emissions in the short term. However, rebounds of energy use can be seen in carbon tax scenarios. Our simulations show that the energy tax works much more gradually, and the rebound effect is not significant. Energy intensity and CO2 emission intensity in all carbon tax scenarios (A1–A3, C1–C3) first show decreases followed by subsequent increases. In contrast, in the energy tax scenario (B), this trend is not observed. CO2 emissions intensity does not exhibit a U-shaped change in all scenarios. CO2 emission intensities in all scenarios monotonically decrease. Combined with other economic indices, this indicates that when energy intensity as well as total energy consumption rebound, CO2 emission intensity continues to decrease, indicating that the energy and carbon tax policies do work to promote “cleaner energy.”

A typical example is the power generation sector. China is still growing rapidly, and the increasing demand for power will induce more emissions. To meet the binding target of emission reduction and still ensure an adequate power supply, the power generation sector has to reduce the CO2 emissions through either technologies[1] such as clean energy technology, CO2 capture and storage technology, and efficiency improvement technology, or other ways like switching energy sources, which will all increase energy costs. The carbon tax would set an explicit price for the CO2 emissions, providing a clear and stable signal to justify investment to adopt cleaner power-generation technology.

The choice of policy instrument should be based on the expected effect of the instrument. For example, the original purpose of both the energy and the carbon taxes was to reduce total energy consumption and CO2 emissions. In terms of reducing CO2 emission intensity, the carbon tax has a very clear effect from the point of implementation, and its effectiveness gradually increases. In contrast, the effect of the energy tax is initially relatively small but grows in the long run. With respect to the tax level, higher rates of both taxes bring larger economic shocks. Therefore, initial tax

---

[1] Although in this study we assume no significant changes in technology or energy structure in the whole time period of the simulation, the technology and energy structure still progresses following the natural course of evolution.

rates could start low to protect sectoral competitiveness and then increase over time to reduce energy use and CO2 emissions.

Energy and carbon taxes are not duplicative. Our analysis very clearly states that if an energy tax and carbon tax are levied simultaneously (scenarios C1–C3), CO2 emission intensity and energy intensity both decrease much more than if only one of the two taxes is implemented, while the impact on employment and outputs are relatively smaller, close to the effect of implementing the carbon tax or energy tax alone.

The energy-intensive sectors are still one of the major driving forces of China's economic growth[1]. In this study, we analyzed the impacts of these two taxes on energy intensive sectors. In general, the non-metallic products processing industry is the most influenced sector, including cement, glass and other products, followed by the metal products processing industry and petroleum products processing industry. These three industries are affected most severely in terms of both output and energy consumption. In contrast to received wisdom, the electricity production and delivery industry suffers the least. This might reflect the fact that compared with the other three sectors, the techniques and technologies of power generation are relatively unitary and the sector has greater technological flexibility because, for example the choice across fossil fuels and renewables represents a much broader fuel portfolio than that available to cement.

With respect to international trade, our analysis indicates that the energy tax carbon taxes influence both total imports and exports, but the effect on imports seems more significant. The sectors using energy as intermediate inputs or raw materials are shocked

---

[1] The annual average contribution of secondary industry to GDP from 2004 to 2013 is 51.6% (data source: National Bureau of Statistics of China http://data.stats.gov.cn/workspace/index;jsessionid=BEF6DA9415820B5442F67FD1197C5E01?m=hgnd)

more than those only using energy as fuels. When we define sectoral competitiveness as the ratio of exports out of total demand, it means “the competitiveness of domestic products in domestic markets.” In the baseline scenario, the CMP of most manufacturing industries are negative—except some light industries such as textiles and wood processing—which means that from the viewpoint of value, domestic industries are less competitive than the international average. However, with the energy and carbon tax policies almost all sectoral CMPs improve, except those of “other petroleum products” and “other coking products” industries. Additionally, similar to the effect on energy intensity and emission intensity reduction, the combined energy and carbon tax policies have greater effects on improving sectoral CMPs than implementing the energy tax only or carbon tax only, and also exert a greater effect than the sum of energy and carbon tax scenarios. Therefore, if improving the competitiveness of domestic industries is one policy target, combined taxation is a good strategy.

For an energy tax or carbon tax policy, the later it starts, the higher the cost incurred to achieve the same amount of CO2 reduction as a policy implemented earlier; in other words, China needs to launch the taxes sooner rather than later to achieve stated reduction targets at a lower cost. Postponing the carbon tax policy requires much higher tax rates and leads to greater economic losses.

In sum, this study conducted a primary analysis on the possible scenarios of introducing an energy tax and carbon tax and obtained some conclusions. However, many important issues still need to be addressed in further researches. For instance, revenue recycling is a key problem determining whether the tax policy is acceptable in practice. Different revenue investments directions, such as in certain sectors or technologies, public infrastructure or residents, decide the costs as well as the effects of emission reduction policies. Different revenue recycling scales, such as at the national or provincial level, decide the development balance of the whole economic system. In addition, maintaining competitiveness of sectors and products in international markets is also important. A complete analysis of international competitiveness requires integrating China’s economy into the global economic and trading systems as well as considering the sectoral characteristics of both domestic and international economies.

Reference

[1]. Baek, C., E.-Y. Jung, et al. (2014). "Effects of regulation and economic environment on the electricity industry′s competitiveness: A study based on OECD countries." Energy Policy **72**: 120-128.

[2]. Bartocci, A. and M. Pisani (2013). "“Green” fuel tax on private transportation services and subsidies to electric energy. A model-based assessment for the main European countries." Energy Economics **40** (supplement 1): s32-s57.

[3]. Baumol, W. J. and W. E. Oates (1998). The Theory of Environmental Policy. Cambridge, Cambridge University Press.

[4]. Chamon, M., K. Liu, et al. (2013). "Income uncertainty and household savings in China." Journal of Development Economics **105**: 164-177.

[5]. Conefrey, T., J. D. F. Gerald, et al. (2012). "The impact of a carbon tax on economic growth and carbon dioxide emissions in Ireland." Journal of Environmental Planning and Management: 1-19.

[6]. Cosmo, V. D. and M. Hyland (2013). "Carbon tax scenarios and their effects on the Irish energy sector." Energy Policy **59**: 404-414.

[7]. Douglas, S. and S. Nishioka (2012). "International differences in emissions intensity and emissions content of global trade." Journal of Development Economics **99**(2): 415-427.

[8]. Du, J., X. Liu, et al. (2014). "State advances and private retreats? — Evidence of aggregate productivity decomposition in China." China Economic Review **In Press, Corrected Proof**.

[9]. Fang, G., L. Tian, et al. (2013). "The impacts of carbon tax on energy intensity and economic growth-A dynamic evolution analysis on the case of China." Applied Energy **110**: 17-28.

[10]. Fischer, C. and M. Springborn (2011). "Emissions targets and the real business cycle: Intensity targets versus caps or taxes." Journal of Environmental Economics and Management **62**(3): 352-366.

[11]. Gerlagh, R. and B. v. d. Zwaan (2006). "Options and instruments for a deep cut in CO2 emissions: carbon dioxide capture or renewables, taxes or subsidies?" The Energy Journal **27**(3): 25-48.

[12]. Guo, J. e., Z. Zhang, et al. (2012). "China’s provincial CO2 emissions embodied in international and interprovincial trade." Energy Policy **42**: 486-497.

[13]. Hammar, H., Å. Löfgren, et al. (2004). "Political Economy Obstacles to Fuel Taxation." The Energy Journal **25**(3): 1-17.

[14]. Han, F., M. Su, et al. (2008). "Primary research on China's energy tax " Review of

Economic Research (Chinese) **55**: 2-13.

[15]. Haufler, A. and M. Mardan (2014). "Cross-border loss offset can fuel tax competition." Journal of Economic Behavior & Organization **106**: 42-61.

[16]. Ifeng (2010) Resorce Taxing Reform and New Energy Policy. Ifeng Finance

[17]. Jenkins, J. D. (2014). "Political economy constraints on carbon pricing policies: What are the implications for economic efficiency, environmental efficacy, and climate policy design?" Energy Policy **69**: 467-477.

[18]. Jiang, K. J., X. L. Hu, et al. (2009). Impact of carbon tax and analysis on related issues. 2050 China Energy and CO2 Emissions Report (in Chinese). J. Z. W. X.L. Hu, L.Y. Cen, H.P. Lei Beijing, Science Press**:** 413-445.

[19]. Jiang, Z. and S. Shao (2014). "Distributional effects of a carbon tax on Chinese households: A case of Shanghai." Energy Policy **73**: 269-277.

[20]. Johansson, O. and L. Schipper (1997). "Measuring the long run fuel demand of cars: separate estimations of vehicle stock, mean fuel intensity, and mean annual driving distance." Journal of Transport Economics and Policy **31**: 277-292.

[21]. Johnson, K. C. (2007). "Refunded emission taxes: A resolution to the cap-versus-tax dilemma for greenhouse gas regulation." Energy Policy **35**(5): 3115-3118.

[22]. Li, Z. (2003). "An econometric study on China's economy, energy and environment to the year 2030." Energy Policy **31**: 1137-1150.

[23]. Liang, Q.-M., Y. Fan, et al. (2007). "Carbon taxation policy in China: How to protect energy- and trade-intensive sectors?" Journal of Policy Modeling **29**: 311-333.

[24]. Lin, B. and X. Li (2011). "The effect of carbon tax on per capita CO2 emissions." Energy Policy **39**(9): 5137-5146.

[25]. Liu, M. and L. Sun (2014). "Policy recommendations on China's energy tax reform " China Petrochem (Chinese) **11**: 46-56.

[26]. Lu, C., Q. Tong, et al. (2010). "The impacts of carbon tax and complementary policies on Chinese economy." Energy Policy **38**(11): 7278-7285.

[27]. Ma, H., L. Oxley, et al. (2009). "Substitution possibilities and determinants of energy intensity for China." Energy Policy **37**(5): 1793-1804.

[28]. MacKenzie, I. A. and M. Ohndorf (2012). "Cap-and-trade, taxes, and distributional conflict." Journal of Environmental Economics and Management **63**(1): 51-65.

[29]. Martin, R., L. B. d. Preux, et al. (2014). "The impact of a carbon tax on manufacturing: Evidence from microdata." Journal of Public Economics **117**: 1-14.

[30]. Mazumder, D. B. (2014). "Biofuel subsidies versus the gas tax: The carrot or the stick?" Energy Economics **44**: 361-374.

[31]. Meleo, L. (2014). "On the determinants of industrial competitiveness: The European

Union emission trading scheme and the Italian paper industry." Energy Policy **74**: 535-546.

[32]. Miller, S., D. Wei, et al. (2010). The economic impact of the Michigan Climate Change Action Plan on the state's economy. Report to the Michigan Department of Environmental Quality. Washington, DC, The Center for Climate Strategies.

[33]. NBS (2011). The national economic and social development statistics report for 2010. Beijing, National Bureau of Statistics of the People's Republic of China.

[34]. NBSNA (2013). Energy Statistical Yearbook of China 2012. Beijing, National Bureau of Statistics and National Energy Administration.

[35]. Ngan, H. W. (2010). "Electricity regulation and electricity market reforms in China." Energy Policy **38**: 2142-2148.

[36]. Parry, I. W. H. and K. A. Small (2005). "Does Britain or the United States Have the Right Gasoline Tax?" The American Economic Review **95**(4): 1276-1289.

[37]. Ren, S., B. Yuan, et al. (2014). "The impact of international trade on China′s industrial carbon emissions since its entry into WTO." Energy Policy **69**: 624-634.

[38]. Richman, D. S., G. Shao, et al. (1993). "Multiregional stock adjustment equations of residential and nonresidential investment in structures." Journal of regional science **33**(2): 207-219.

[39]. Rose, A., D. Wei, et al. (2011). "Regional macroeconomic assessment of the Pennsylvania Climate Action Plan." Regional Science Policy & Practice **3**(4): 357-379.

[40]. StateCoucil (2012) the 12th five-year plan on energy saving and emission reduction. the central government report

[41]. Sterner, T. (2007). "Fuel taxes: An important instrument for climate policy." Energy Policy **35**(6): 3194-3202.

[42]. Sterner, T. (2012). "Distributional effects of taxing transport fuel." Energy Policy **41**: 75-83.

[43]. Wang, J., G. Yan, et al. (2009). "The study on China's carbon tax policy to mitigate climate change." China Environmental Science (in Chinese) **29**(1): 101-105.

[44]. Wang, Z.-X. and Y.-Y. Wang (2014). "Evaluation of the provincial competitiveness of the Chinese high-tech industry using an improved TOPSIS method." Expert system with applications **41**: 2824-2831.

[45]. Xin Wang, J. F. L., Ya Xiong Zhang (2011). "An analysis on the short-term sectoral competitiveness impact of carbon tax in China." Energy Policy **39**(7): 4144-4152.

[46]. Zhang, K. H. (2014). "How does foreign direct investment affect industrial competitiveness? Evidence from China." China Economic Review **30**: 530-539.

[47]. Zhang, Z. and A. Baranzini (2004). "What do we know about carbon taxes? An inquiry into their impacts on competitiveness and distribution of income." Energy Policy **32**:

507-518.

[48]. Zhou, N., M. D. Levine, et al. (2010). "Overview of current energy-efficiency policies in China." Energy Policy **38**: 6439-6452.

Chapter 6

Assessing the Economic and Environmental Impacts of Raising China's Emission Standard for Thermal Power Plants: An CGE Model-Based Analysis

Yu LIU[1], Xiaohong HU[2] and Bo MENG[3]

Abstract: Thermal power plants are considered as the main source of atmospheric pollutants in China due to their massive emissions of sulfur dioxide (SO_2) and nitric oxide (NO_X). In order to enhance the environmental protection, the Ministry of Environmental Protection of China has introduced a new emission standard of atmospheric pollutants for thermal power plants on January 1, 2012. Issues concerning how and to what extent this new standard may impact on Chinese economy and environment have caused extensive concerns in related governmental and academic circles. As a response to this issue, a Computable General Equilibrium (CGE) model-based analysis is conducted in this paper. The model simulation results show that imposing the new standard may cause about 1.33% fall of GDP in the target year. In terms of changes in prices and domestic demand structure, the new policy can make contribution to curbing inflation and making the domestic demand structure more environmentally friendly. The new standard also leads to the output increase for private consumer goods and other labor-intensive industries due to the decreasing labor cost. The effect on air pollutants emissions reduction is also remarkable. The emissions of SO_2 and NO_X may decrease by 21.89% and 13.18% respectively, with the absolute amounts being reduced by

572.42 and 170.76 ten thousand tons. This is the result of increasing the removal rate increases and the sharp decline of the coal combustion emissions.

Key words: Thermal power plant; emission standard; macro-economy; CGE model

1. Institute of Policy and Management, Chinese Academy of Sciences, Beijing, China, 100190;

2. School of Management and Economics, Beijing Institute of Technology, Beijing, China, 100081;

3. IDE-JETRO

1. Introduction

Chinese economy has experienced a high speed growth accompanied by a very fast-paced industrialization and urbanization. There is no doubt that China has made significant achievements in the economic development, but the increasing pressure coming from the environmental side has been rising. For example, the Chinese electric power industry has grown into the second largest in the world, with installed capacity rising from 1.85 GW in 1949 to 713.29 GW in 2007 and an average annual growth rate of 10.8%. The majority of generation plants are either coal-fired —almost 78% of the total capacity in 2007 —or hydro powered —over 20%. Nuclear plants account for only about 1% of the capacity (Russell Pittman, 2010). Atmospheric emissions from electricity generators are a major contributor to such pollution problems as acid rain and fine particle concentrations in the atmosphere mainly due to sulfur dioxide (SO_2) emissions, and depletion of ground-level ozone mostly from nitrogen oxides (NO_x) emissions (Dallas Burtraw et al., 2005). In order to achieve the emissions reduction target, the Ministry of Environmental Protection of China has introduced the Emission Standard of Atmospheric Pollutants for Thermal Power Plants (ESAPTPP2011) on January 1, 2012. The new standard impacts on not only the emissions level but also the economic system by various channels such as the change of market prices of goods and services. For policy makers, it’s important to know: How large is the economic cost (e.g. GDP loss) when imposing this new standard? How will the market prices and domestic consumption structure change, and to what extent? Can the goal of reducing pollution and saving energy be achieved under this new standard? If yes, what kind of energy product contributes most to the emissions reduction? How will the industrial structure change, to what extent? These questions are all urgently to be answered.

At present, there are mainly two strands of researches in studying the influence of the ESAPTPP. One strand focuses on the technology- or strategy-oriented issues concerning how to reduce pollution and save energy in thermal power industry through qualitative analyses or case studies (Sun, 2001; Shang *et al.*, 2007; Jin et al., 2009; Fu, 2011; Sun, 2012; Tan, 2014). The other one focuses on the economic side by using various models, such as the emissions trading model (Wang, 2005; Wang, 2007), mathematical model (Liu, 2007), comprehensive air quality model (Sheng, 2011; Du, 2013; Wang, 2013) and so on. Most of the existing literature relating to the ESAPTPP mainly addresses the technical issue with few discussion on its economic impacts. Compared to the previous studies, this paper focuses on elucidating the generation and emissions reduction mechanism of SO_2 and NO_X in the whole economic system and simulates the comprehensive impacts of the new standard on Chinese economy and environment during the period of the twelfth five-year plan based on an extended CGE model. In addition, this paper integrates the firm-level micro information based on a large scale enterprises survey (the 2007 pollutant census database [1] into the conventional input-output database. This helps us improve the quality and reliability of parameter calibration in the CGE model used in this study.

---

[1] On February 6, 2012, the National Bureau of statistics decided to carry out the first national census of pollution sources in order to strengthen the supervision and management of the environment. Census of standard time was December 31, 2007 and the standard period was 2007. The census object was the discharge of pollutants within the territory of China including the industrial pollution sources, agricultural pollution sources, living pollution sources and centralized pollution treatment facilities. The Survey content included the basic situation of all kinds of pollution source, the generation and emissions of main pollutants, and pollution treatment, etc. The pollutant database this paper adopts is the 2007 input-output table department through the original classification of national economic industries, simultaneously, combined with all kinds of life source pollution census data of 2007, which comprehensively tease out the production and emission of waste gas of 135 industries using 5 energy products (coal, oil gas, petrol, coking, electricity and gas), combined with other related data.

2. The Main Content about the Emission Standard of Atmospheric Pollutants for Thermal Power Plants

The Ministry of Environmental Protection of China published the ESAPTPP2003 on January 1, 2004, including emissions limits on three kinds of pollutants, soot, SO_2 and NO_X. The key control is to promote thermal power flue gas desulfurization. The implementation of the standard has played an important role in controlling emissions of atmospheric pollutants, protecting the environment and promoting technological advancement of the power industry. The Smoke and SO_2 emissions from electric power were supposed to be controlled more effectively under the ESAPTPP2003. However, with the increasing emissions of NO_X, the sulfuric acid rain pollution has been turned into a mixed pollution of sulfuric acid and nitric acid rain. The urban atmospheric environmental situation in China is still grim, regional air pollution problems have become more significant than ever. Additionally, NO_X emissions and its control requirements in the EASPTPP are very different from developed countries. The standard in the ESAPTPP2003 is no longer able to fulfill the requirements of the environmental protection and improve emissions control in the thermal power industry at the present time or in the future. Considering that the demand for controlling on NO_X emissions for the thermal power plants is imminent, the EASPTPP2003 need to be revised accordingly. Therefore, the new version of the standard EASPTPP2011 was issued. In addition to the above three pollutants, mercury and its compounds are also under the limitation and control[1] in the new standard. In this paper, however, we focus on the two

---

[1] The data comes from the Emission Standard of atmospheric pollutants for Thermal Power Plants (GB13223-2003) revised version.

most important polluting emissions: SO_2 and NO_X. In the new standard, the emission concentration of SO_2 is controlled in 100mg per m3 for new thermal power boilers and gas turbines (the existing thermal power boilers are still in 200mg per m3). For NO_X, the newly built and the existing thermal power boilers which have been approved by environmental impact assessment from January 1, 2004 to December 31, 2011 must fully implement the flue gas denitrification so that the emission concentration of NO_X should be controlled within 100mg per m3. For those that are approved before December 31, 2003, the limit concentration of NO_X should be within 200mg per m3.

3. Model and Data

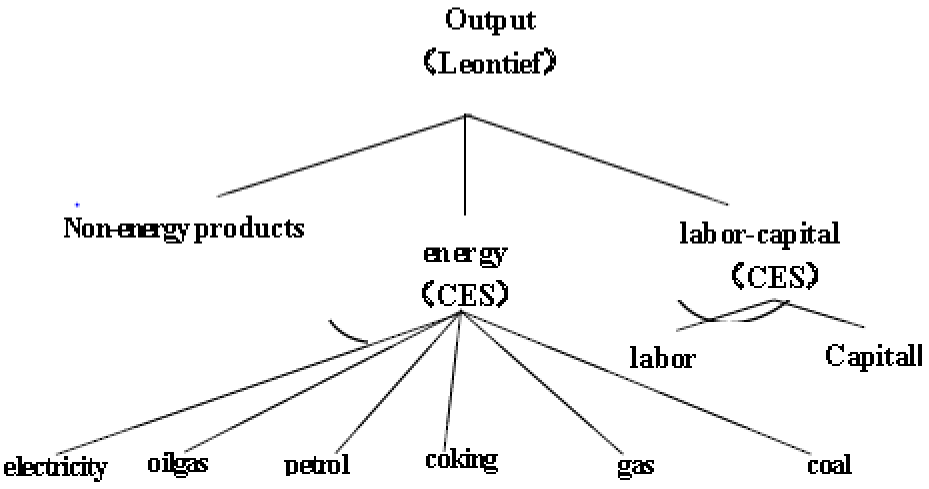
CGE models have been widely used in policy impact analyses (reference?). This paper adopts the static CGE model developed jointly by Institute of Policy and Management, Chinese Academy of Sciences and Center of Policy Studies, Victoria University for Chinese economy. The model includes 135 industrial sectors, 3 kinds of primary factors (labor, capital, land) and six economic agents (product, investment, household, export, government and stock). The model also considers 4 kinds of margins, including transportation cost by modes (water, air, rail, road, and pipeline), insurance, trade (wholesale, retail), and warehousing (Dixon and Maureen 2002）.

(1) **The setting of the closure.** This paper adopts long-term closure hypothesis, because an investment of desulfuration or denitration in gas needs several years from investing to successful operating. The short-term closure is not suitable in this case. The specific conditions of long-term hypothesis are as follows. 1) Labor market. In the long-term closure, the level of employment depends on the birth rate, death rate, labor participation rate and population. Therefore, we assume that the total employment keeps

constant in the long term, and the labor demand depends on wage rate. 2) Capital market. In the long-term closure, capital can move across industries based on the level of rent. Therefore, long-term closure hypothesis is accompanied by capital adjustment, making the different rate of capital return convergence to the same level. 3) Investment market. In the long-term closure hypothesis, the investment is determined by capital stock. 4) Consumer behavior. Generally speaking, the expenditure is decided by the income level. So both government consumption and household consumption depend on a common utility function subject to the disposable income, and both positively correlated with income. 5) Trade balance. In the long-term closure, we assume the ratio of nominal trade balance and nominal GDP keep constant.

(2)**The introduction of pollutants discharge module.** Considering the rigid demand of energy input in China's current condition (Xie *et al.*,2000; Lin *et al.*， 2012), this paper still assumes the energy as the intermediate input into production in the model (Figure 1). The intermediate input is the aggregation of energy intermediate input and non-energy intermediate input. The intermediate input is nested through a Leontief function which is featured with fixed ratio of different inputs. The substitution relationship between different energy inputs is described by CES function. Energy sectors produce energy goods which are divided into electricity power, coal, oil gas, coking, petrol and gas.

Figure1 Production Nest of the CGE Model



The Intermediate input factors of energy equation are as follows:

$$X_j = \underset{i=1}{\overset{6}{CES}}\{\frac{X_{ij}}{A_{ij}}; \rho_j, b_{ij}\}$$

The equation expresses the CES composite of domestic goods and imported goods used by j industry. Among them, X_j denotes the amount of energy product used by j industry. X_{ij} is the production of j industry using energy product i which comes from domestic goods and imported goods. A_{ij} denotes the technical parameters of j industry using energy product i. b_{ij} is the share parameters of j industry using energy product i. ρ_j is constant elasticity of substitution of j industry using energy product. If energy product i is used for the energy industry. the elasticity of substitution is 0. Taking the thermal power industry as an example, the thermal power industry mainly depends on coal to generate electricity power; therefore, coal is the main intermediate input, and it cannot be substituted with other energy product. But generally speaking, the energy substitution refers to inter-fuel substitution. If energy product i is used for non-energy industry, the elasticity of substitution is 0.5, which is generally in line with the elasticity of substitution of GTAP-E model (Jean-Marc Burniaux, 2002).

Considering the necessity for thermal power industry to do purification treatment according to the emissions standard, we set up the variable of exhaust removal rate[1]. Meanwhile, the model separates the exhaust emissions into the ones from combustion and the ones from processing for different industries with different energy. The emissions from combustion refer to the emissions produced by burning a kind of fossil energy (coal, oil gas, petrol, et al) during the production process. Similarly, the emissions from processing are defined as emissions produced by some specific craft process during the production process. The emissions from processing are related to the level of industrial output. In other words, if the industrial output keeps constant, the amount of emissions will keep constant as well. The related function is as follows:

$$p_i = x_i * \omega_i$$

p_i is the emissions from processing by industry i. x_i is the output by industry i. ω_i is the exhaust removal rate of emissions from processing for industry i.

Nevertheless, the emissions from combustion change with the amount of burning fossil energy at the same level. Given the substitution between different energy inputs, the mechanism of polluting emissions reduction caused by the change of energy inputs can be modeled. The specific function is as follows:

---

[1] Exhaust removal rate=emission of waste gas/production of waste gas, describes the difference between the production and emission of exhaust gas.

$$b_j = x1_{ij} * \alpha_j$$

b_j is the emissions from combustion by industry j. $x1_{ij}$ is the emissions produced by industry j using energy i. α_j is the exhaust removal rate of combustion emission for industry j.

(3) **The design of simulation.** Following the long-term closure hypothesis, this paper simulates the impacts on economic performance and pollutants reduction caused by the thermal power industry from three channels. (1) Investment-driven[1]. The investment of thermal power industry in the devices of denitration and desulfuration will drive their upstream industry to expand, and then will positively impacts on relevant upstream industries. (2) Cost-driven[2]. The thermal power industry will increase investment cost and operating cost to reach new emissions standard, and it will reduce the output of thermal power industry. (3) Changes in the exhaust removal rate[3].

---

[1] The manual of *Emission Standard of atmospheric pollutants for Thermal Power Plants* (author, year??) reveals that the thermal power capacity installed is 55.442 million KW and 107 million KW in 2007 and 2015 separately. This can help us get the increasing rate of thermal power capacity (92.99%). In addition, the investment of other special equipment manufacturing industries on the thermal power was 20.894 billion Yuan RMB in 2007. Based on this information, we assume that the investment of other special equipment manufacturing industries on the thermal power for 2015 will be 40.324 billion Yuan RMB. However, according to relevant researches, the total demand of investment will be 212 billion Yuan by 2015 (17 billion Yuan for SO_2 and 195 billion Yuan for NO_X), therefore, the growth rate of investment should be 425.7.

[2] The manual of Emission Standard of atmospheric pollutants for Thermal Power Plants reveals that the investment devices of denitration and desulfuration is 212 billion Yuan RMB, operating cost of that is 71 billion Yuan RMB aiming at the emission standard of NO_X and SO_2 in 2015. In the 2007 Chinese input-output table, the output of thermal power industry is 3148.599 billion Yuan RMB, and we assume the increasing rate of thermal power capacity installed approximately equals to the increasing rate of output of thermal power industry, therefore, the output of thermal power industry is 6076.622 billion Yuan. Then the change of production tax rate is 4.657%.

[3] In theory, the removal rate of emissions in thermal power industry is 90% and 25% for desulfurization and denitration respectively. The manual reveals that thermal power capacity installed will reach 1.07 billion KW in 2015, 0.131 billion KW needs desulfurization, and 0.817 billion KW needs denitration. In other words, at present, 0.939 billion KW and 0.252 billion KW has been dealt with. The share of dealing is 87.8% and 23.6% respectively. Multiplying by the removal rate in theory, we can get the real exhaust gas removal rates, 78.98% and 5.91%. The remaining shares of SO_2 and NO_X are 21.02% and 94.09%, respectively. If devices of denitration and desulfuration will cover all in 2015, the removal rate in theory will reach 90% and 25%. Then, the remaining shares in theory will be 10% and 75%. Then,

Investing in the devices of denitration and desulfurization increases the removal rate of emissions greatly, thus reducing the polluting emission and strengthening the force of ending treatment. In short, the exogenous variables we shock are the investment of thermal power industry in the devices of denitration and desulfurization, production tax rate of thermal power industry, and the end treatment removal rate of emissions for the thermal power industry. By shocking the three variables, we simulate the economic and pollutants reduction effects of imposing the new standard.

The economic database used is based on the Chinese 2007 input-output table for 135 sectors published by National Bureau of Statistics of China. The environmental database is based on the pollution census data for 2007 published by the Ministry of Environmental Protection of China, including the main atmospheric pollutants (SO_2 and NO_X) emission data at the 135-industry level.

Table 1 Impact on China's Macro Economy

Unit: %

Items	change
Macroeconomic Variables	
GDP	-1.33
CPI	-0.28
Household Consumption	-0.80
Investment	-2.00
Export	-0.42
Import	0.18
Real Rate of Exchange	-0.18
Term of Trade	0.11
Factor Market	
Capital Stock	-1.91

---

divide the remaining shares after installing by the remaining shares before installing, we get -52.4% and -20.3%.

Real Wage	-2.71

Data Source: Simulation of CGE model.

4. Analysis of Simulation Results

4.1 Macro-economic Impacts

(1) The model result reveals great negative impact on the economy caused by increasing the emissions standard of thermal power industry. The simulation shows that the growth rate of China’s GDP will be slowed down by 1.33%. If the growth rate of GDP is measured as 7.8% in 2012 in China, its magnitude of the fall approximately equals to 8-weekeconomic stagnation. Decomposing GDP from expenditure side, the result reveals that the reason of GDP fall is mainly due to the investment change (-0.77%). In the long term, the return rate of capital, employment, and technological advance keeps constant, the reduction of capital stock (-1.91%) will drive down the investment, and it will then affect the growth rate of economy. (2) For the commodity price change, the simulation result shows that CPI will change by -0.28%. Therefore, increasing the emissions standard of thermal power industry doesn’t jack up price. On the contrary, it will restrain the price. There are two reasons. First, improving production tax rate of thermal power industry will increase the cost of thermal power industry, and it will increase the price of electricity directly. However, the increase of price of this kind of intermediate input will transmit to industries which use large amount of electricity directly, such as basic chemical raw materials manufacturing, ferroalloy smelting industry, non-ferrous metals mining and dressing and ferrous metals mining and dressing. There is just limited effect on household consumption goods (real estate, household appliances, food). On the other hand, due to the reduction of real wage and labor cost, the price of household primary consumption goods falls (agriculture,

light industry, service industry).

(3) Increasing the emissions standard of thermal power industry also impacts on China’s exports and imports. Due to the depreciation of real exchange rate (-0.18%), i.e. domestic currency appreciate, the exports price increases compared with international market. The exports reduce by 0.42%. However, we assume the imports price keep unchanged, the imported goods are therefore cheaper. This leads the imports to increase by 0.18%.

(4) Increasing the emission standard of thermal power industry has positive impact on the structure change of domestic demand. The simulation results reveal that the household consumption and investment reduce by -0.80% and -2.00% separately. The main reason of the reduction of household consumption is the reduction of GDP which causes national income to reduce. Compared with the small amount of private consumption, the amount of investment reduces more. This is mainly due to the capital stock reduction (-1.91%). In the domestic demand structure, the share of reduction in private consumption is less while investment is much bigger. With the new standard, investment decreases much more than consumption both in percentage terms and in absolute amount. Therefore, increasing the emissions standard of thermal power industry can improve the domestic demand structure in China to some extent.

(5) The level of employment, in the long-term, keeps unchanged. Due to the reduction of capital stock, the marginal output of labor (-1.19%) will reduce. Producers decide on the amount of factors depending on the capital rent and wage level that they face. On one side, due to the reduced real wage, the demand of labor will increase. On the other hand, affected by the thermal power industry production tax directly or indirectly, the demand of labor in relevant industries will reduce, and labors move

between different industries.

4.2 Impacts on the Industry level

The increase of the production taxes on thermal power industry will raise the production costs and drive electricity prices up, thus influencing on its upstream and downstream industries. The increasing demand on other special equipments will increase the production, thus exerting a further impact on its upstream and downstream industries. In addition, other industries, which do not directly link to the power and other special equipments manufacturing, will also be affected through indirect channels such as the changes in labor market, capital market and trade patterns.

4.2.1 The Major "Losers"

Figure 2 shows the changes of the 10 biggest shocked industries. The output of thermal power industry falls by 4.37%. Most of these damaged industries are capital-intensive industries, such as basic chemical raw materials manufacturing (-4.19%) [1] , ferroalloy smelting (-2.98%), non-ferrous metal mining (-2.78%), non-ferrous metal smelting (-2.61%), ferrous metal mining (-2.34%), transmission and distribution and control equipment manufacturing (-2.32%), non-ferrous metal rolling processing (-2.04%), building materials manufacturing (-1.96%) and Construction (-1.90%). Although these industries' outputs have been shocked greatly, the reasons for the decline of their outputs vary. The impacts on industrial output can be divided into three categories:

(1) Direct impacts. The thermal power industry is shocked directly, and the extent of damage is the biggest. Increasing the production tax rate of thermal power industry will push up the cost of thermal power industry directly, thus causing the price of

---

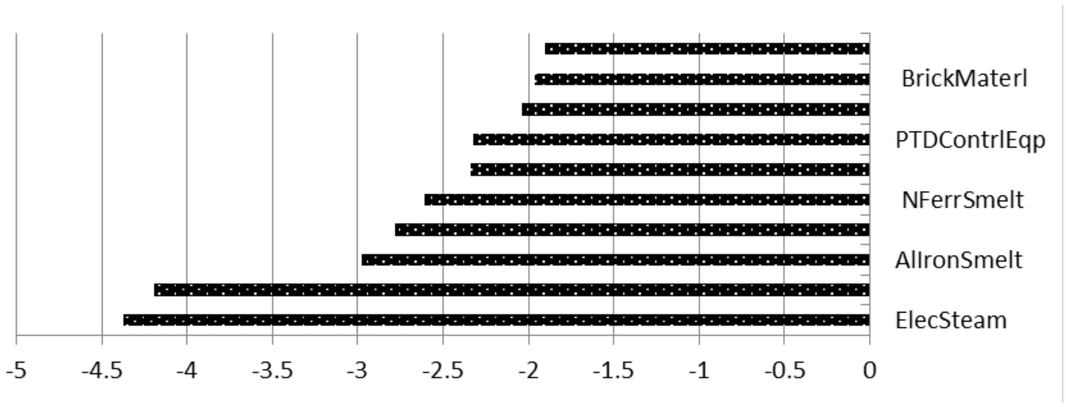
[1] The bracket means the percentage of change.

electricity to increase. Since 96% of the electricity is used as intermediate input, the increased electricity price will transmit to the downstream industries to shrink that use large amount of electricity.

(2) Economic impacts through downstream inter-industrial linkages. The negative impact of the increased cost of upstream industries on downstream industries is mainly that the increased price of electricity directly pushes the cost of downstream industries so high that the downstream industries have to reduce the output. The biggest losers in the downstream include basic chemical raw materials manufacturing, ferroalloy smelting, non-ferrous metal mining, non-ferrous metal smelting, ferrous metal mining, and non-ferrous metal rolling processing

(3) Economic impacts through upstream inter-industrial linkages. Investment changes impacts on the upstream industries, like construction. Since 94% output of construction industry depends on the level of investment. The reduction of total investment first impacts on construction, then further onto other upstream industries, like building materials manufacturing and transmission, distribution and control equipment manufacturing, since the outputs in these two industries are mainly used as intermediate inputs in the construction industry.

Figure2 Output Changes of Main Damaged Industries (%)



Data Source: Simulation of CGE model.

4.2.2 The Major "Winners"

The top 10 benefited industries are shown in Figure 3. The output of other special equipment manufacturing increases the most, by 9.09%. Other benefited industries mostly belong to labor-intensive industries, such as aquatic products processing (1.71%), leather products (1.14%), knitwear manufacturing (0.89%), wool textile (0.68%), slaughtering and meat processing (0.55%), fishing (0.41%), forest (0.39%), gas supply (0.33%) and textile manufactured goods manufacturing (0.31%). According to the different mechanism of the shock transmission, the reasons are divided into several categories as follows.

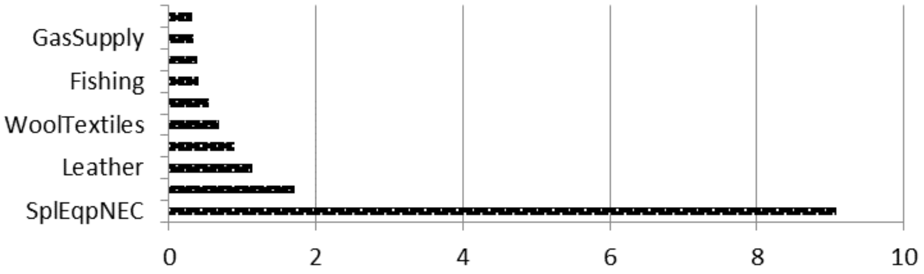
(1) Direct impacts. The most benefited industry is the “Other special equipment manufacturing”. In order to fulfill the new standard, the thermal power industry should introduce more other special equipment which accounts for about 50% in its total investment. As a result, the output of the other special equipment manufacturing will increase.

(2) Cost advantage from the falling of labor wage. Forestry, livestock and fishing are labor-intensive industries. The labor share of the total value added in these three industries all accounts for more than 95% respectively. Therefore, the falling of labor wage will drive the product price of these industries to fall as well, and the output will expand benefiting from the decreased factor prices.

(3) Impacts through upstream and downstream inter-industrial linkage on exports. Livestock and fishing are the main inputs for slaughtering and meat processing and aquatic products processing (76%and 69%). Besides, the main input of leather products is slaughtering and meat processing. The decreased price of intermediate input leads to these three industries to reduce the production cost. Thus, Upstream and downstream inter-industrial linkage effects make slaughtering and meat processing, aquatic products processing, and leather get further advantage of the reduction of cost, and drive exports of these goods to increase. Meanwhile, the knitwear manufacturing and textile manufactured goods manufacturing are also benefited due to the falling of domestic price and higher share of export (89% and 44%, respectively).

(4) The pulling effect of the downstream industry. The rapid expansion of export-oriented industries will also pull their upstream industry output to increase. For example, the wool textile will be benefited since its products are mainly used as the main intermediate inputs in the knitwear manufacturing and textile manufactured goods manufacturing industries.

Figure 3 Output Changes of Main Benefited Industries (%)



Data Source: Simulation of CGE model.

(5) The substitution effects of energy prices. The increase of output of gas production and supply mainly attributes to the substitution effect of energy prices. The energy products, a kind of intermediate input, link with other intermediate inputs through Leontief function. However, the relation between energy products is described by CES function, and different energy products can substitute with one other. Compared with the price of thermal power industry and other energy industries, the prices of gas and coal do not shift so much.[1] For example, the price of coal falls by 0.07%, and gas increases the least by 0.07%. Therefore, firms will choose the energy products of gas and coal to substitute the relatively more expensive energy products. However, the output of coal industry is limited due to the shrink of the downstream heavy industries. Therefore, compared with other energy products, the outputs of gas production and supply increase more.

4.3 **The impact on emissions of air pollutants SO_2 and NO_X**

The new standard of thermal power plant does not only shock the economy, but also significantly reduce emissions of atmospheric pollutants level. The simulation

---

[1] More detailed discussion of the price changes of gas and coal is provided later in Section 4.3.

results show that the emissions of SO_2 and NO_X decrease significantly with the production decreasing a smaller quantity in percentage terms. The emissions of SO2 and NO_X are decreased by 21.89% and 13.18% (absolute amount decrease by 572.42 and 170.76 ten thousand tons), with production amount being reduced by 0.67% and 2.24% (absolute amount decrease by 94.08 and 29.83 ten thousand tons). This is because the installment of the device of desulfuration and denitration improve the combustion removal rate for thermal power industry, thus leading to a dramatic decline in emissions from thermal power industry.

For the end users, almost all of the emissions are reduced from the emissions of intermediate industries. The emissions of SO_2 and NO_X fall by 23.05% (571.25 ten thousand tons) and 13.6% (170.38 ten thousand tons), respectively, through intermediate industries, while the consumer use fall by only 0.85% (1.16 ten thousand tons) and 0.86% (0.37 ten thousand tons), respectively. As for the emissions channel, the reduced emissions of combustion of fossil energy is the main reason for total reduction of emissions, as the proportion of the emissions from processing is very small (less than 1%). The percentage and absolute amount of emissions reduction from combustion and processing are roughly the same as intermediate and consumer use. The emissions of SO_2 and NO_X are decreased by 23.37% (569.00 ten thousand tons) and 13.67% (169.81 ten thousand tons), respectively, and the emissions from processing are only 1.9% (3.42 ten thousand tons) and 1.76% (0.95 ten thousand tons).

Emissions from combustion are generated by the use of coal, oil gas, petrol, coking and gas, the terminal using of the electricity power does not produce SO_2 and NO_X. Therefore, among the varieties of energy products, the emissions from combustion of coal has the biggest contribution to the total emissions reduction while other energy products contribute less. Results show that the emissions of SO_2 and NO_X decline by 438.74 and 164.84 ten thousand tons, respectively, because of using coal, which account for 77.11% and 97.07% of the total emissions from combustion. The second largest contributors are oil gas and petrol. For oil gas, the emissions of these two kinds of air pollutants are decreased to 125.58 and 0.52 ten thousand tons, while the emission of petrol drops 4.29 and 4.18 ten thousand tons, respectively. Generally speaking, the new standard of reducing emissions is mainly effective to reduce the use of coal and therefore emissions from coal combustion by industry. But it may be different industry by industry. Therefore, in order to in-depth analyze the change of SO_2 and NO_X emissions at the industry level, this paper illustrates the changing trends and reasons of SO_2 and NO_X emissions for different industries.

Table 2 impacts on the air pollutants of SO_2 and NO_x

	SO_2		NO_x	
	Percentage（%）	Absolute (ten-thousand tons）	Percentage（%）	Absolute (ten-thousand tons）
Total production	-0.67	-94.08	-2.24	-29.83
Total emission	-21.89	-572.42	-13.18	-170.76
Way of use（emissions）				
Intermediate use	-23.05	-571.25	-13.6	-170.38
Consumption use	-0.85	-1.16	-0.86	-0.37
Way of discharge（emissions）				
Process emissions	-1.90	-3.42	-1.76	-0.95
Combustion emissions	-23.37	-569.00	-13.67	-169.81
Energy products（combustion emissions）				
coal	-30.90	-438.74	-15.32	-164.84
oil gas	-22.98	-125.58	-6.37	-0.52
petrol	-1.23	-4.29	-4.13	-4.18
coking	-0.33	-0.40	-0.33	-0.15
gas	3.42	0.01	-1.09	-0.11
electricity	0.00	0.00	0.00	0.00

Data Source: Simulation of CGE model.

The change of industry emission has a close relationship with its energy structure and the substitution between different energy products which is due to the relative price changes. Therefore, this paper first needs to clarify the reasons why the six energy products change before analyzing the industry results. The simulation results demonstrate that only the price of coal falls (-0.07%) and the other five energy products' prices rise in various degree. For the price of coal, there are two main reasons. On the one hand, the decreased output of downstream thermal power industry causes the demand of upstream coal industry to decline. On the other hand, the coal industry belongs to labor-intensive industry. The falling price of labor wage will drive the cost of coal industry to decline relatively. The price of electricity power (13.52%) rises because the investment of new emission standard will drive the production cost of thermal power industry to increase in the long run[1]. As for oil gas, petrol, coking and gas, their prices rise due to the increasing upstream cost promoting their production cost. Among them, the rising prices of oil gas and coking (0.29% and 0.72%) is mainly due to the upstream industry electricity power price rise, while the prices of petrol and gas (0.23% and 0.07%) rise because the increasing upstream oil gas industry's price increases.

4.3.1 Impacts on SO_2 emissions of major industries

In order to facilitate the analysis of the change of industries'SO_2 emissions, we select the top 5 industries with increased and decreased emissions. Generally speaking, the change of SO_2 emissions depends on three essential factors: changes of industries

---

[1] Because the short-term investment in the thermal power industry will relate to repay the loan and interest payment problems, therefore, the relevant expenses will be reflected in the enterprise's production cost to a certain extent.

output, substitution between energy products caused by relative price changes, and the initial total emissions and share of industries.

Table 3 changes of SO2 of major industries

	TE	PE	CE	coal	oilgas	petrol	coking	gas
Top 5 decreasing industries								
elecsteam	-582.14	-0.01	-582.14	-444.93	-127.69	-9.47	-0.05	0.00
basicchem	-1.27	-0.37	-0.90	-0.18	-0.64	-0.02	-0.06	0.00
ironsmelt	-1.04	-0.34	-0.70	-0.22	-0.02	0.00	-0.45	0.00
nFerrSmelt	-0.73	-1.38	0.65	0.42	0.11	0.03	0.09	0.00
brickMaterl	-0.43	-0.20	-0.23	-0.10	-0.10	-0.01	-0.02	0.00
Top 5 increasing industries								
crops	3.76	0.00	3.76	0.20	0.00	3.55	0.00	0.01
paperProd	1.84	0.00	1.85	1.52	0.27	0.05	0.00	0.00
cottonTextil	1.19	0.00	1.19	0.64	0.53	0.03	0.00	0.00
fishing	0.84	0.00	0.84	0.01	0.00	0.83	0.00	0.00
cement	0.76	-0.13	0.89	0.84	0.04	0.01	0.01	0.00

Data Source: Simulation of CGE model.

Note: TE=PE+CE, TE means total emissions, PE means process emissions, CE means combustion emissions.

CE= coal + oil gas+ petrol + coking +gas

In general, the change of industries’ SO_2 emissions presents two significant characteristics (see table 3). First, the emissions reduction is highly concentrated in one industry while the emissions increment comes from various industries which are dispersedly distributed. Among industries with decreased emissions, thermal power industry’s emission declines the most, reaching 582 ten thousand tons, while the other 4 industries’ total emissions reduce by less than 5 ten thousand tons (basic chemical raw materials manufacturing industry drops by 1.27 ten thousand tons, iron-smelt industry falls by 1.04 ten thousand tons, non-ferrous metal smelting industry drops by 0.73 ten thousand tons and Brick materials manufacturing industry decreases by 0.43 ten thousand tons). This is because 43% of the industry's total emissions come from thermal power industry, whose emissions base is very big, therefore, with a very small change of output can lead to large fluctuations in emissions. Different from industries with a decrease in emissions, industries with an increase in SO_2 emissions is relatively dispersed. Among them, agriculture ranked as first and cement manufacturing ranked as fifth, increasing by 3.76 and 0.76 ten thousand tons, respectively. There is only a gap of 0.3 ten thousand tons between these two industries.

Second, for the emissions channel, emissions from combustion basically play a leading role, while the emissions from processing contribute less. The simulations results show that among the top 10 biggest changes of industries' SO_2 emissions, except non-ferrous metal smelting industry, the other 9 industries' emissions from combustion play a compelling role. Baseline database shows that the emissions of these industries mainly comes from combustion of energy, while emissions of processing is very small. For example, the agriculture and fishing have no emissions of processing, and that of thermal power industry, papermaking and cotton and textile industry are less than 1% of its total emissions(emissions from combustion + emissions from processing), the emissions from processing of cement and brick materials manufacturing industry are less than 10% of the total emissions. This share in basic chemical raw materials manufacturing and the iron smelt is relatively high, reaching 16% and 23%, respectively. The share of these industries' emissions from processing is consistent with its contribution to the change of total emissions. Different from other industries, the emissions from processing of non-ferrous metal smelting industry accounts for more than 79%. In this case, the emissions from processing plays a dominant role in its total emissions change.

As thermal power industry is directly shocked, its emissions reduction is the maximum, therefore, it deserves a further explanation. The decrease of thermal power industry's emissions almost entirely comes from the decline of emissions from combustion, while the emissions of procession changes very little. This is because in the baseline database, thermal power industry's combustion emissions accounts for 99.8% of total emissions. Therefore, even though the industry outputs vary greatly (-4.4%), the contribution of emissions from processing in the total emissions is still small. The model shows that the emissions from combustion of thermal power industry decreases by 582 ten thousand tons, but the emissions from processing only drop by 85 ten thousand tons. This is because the thermal power industry increases its combustion emission removal rate, resulting in a substantial decline in emissions from combustion. That is to say, emissions reduction is not primarily due to the reduced energy use, but the increased gas removal rate. Looking at the types of energy products, coal and oil gas are the most important inputs of thermal power industry. Therefore, its decrease of emissions from combustion mainly comes from the decline emissions from coal (-445 ten thousand tons) and oil gas (-128 ten thousand tons). In addition, there exists no energy substitution effect in the thermal power industry, because coal is the most important intermediate input which is not simply used to burn.

Finally, there are also two industries (non-ferrous metal smelting industry and cement manufacturing) deserving some explanations, because their changes of emissions from combustion and processing are different from other industries. For most industries, the two types of emissions are changing in the same direction, but in these two industries emissions from processing decline while emissions from combustion increase. For example, the total emissions of non-ferrous metal smelting industry decreases by 0.73 ten thousand tons, of which, the emissions from processing decrease by 1.38 ten thousand tons, and the emissions from combustion increase by 0.65 ten thousand tons. The former declines because of the output contraction (-2.6%), while the latter rises because in its energy use composition, electricity power’s share is very high, reaching 65%. Therefore, the average price of energy is pushed up by increasing electricity price, resulting in a substantial increase in the use of other five types of energy. This increase is more than the decline in output. However, the end use of electricity power does not produce emissions, hence, the emissions from combustion in the five energy goods increase. While coal and petrol are the main intermediate inputs of non-ferrous metal smelting industry, these two energy inputs contribute more to its emissions from combustion. Cement manufacturing industry and paper industry face the same situation as shown in the table.

4.3.2 Impacts on NO_X emissions of major industries

In general, except thermal power industry, the changes of NO_X emissions in other industries are small. The reasoning is almost the same as SO_2, yet a bit different. Therefore, we will focus on the comparison of the two kinds of emissions.

First, from the perspective of industry coverage, changes of NO_X and SO_2 emissions from industry sources are basically the same. In the top 5 industries with decreasing NO_X emissions, 4 industries remain same as with SO_2 emissions (thermal power industry, basic chemical raw materials manufacturing industry, ironsmelt industry and brick materials manufacturing industry); and in the top 5 industries with increasing NO_X emissions, 3 are the same industries (cement manufacturing, paper and textile industry) as with SO_2 emissions. It can be seen that NO_X and SO_2 emissions share similar generation mechanism.

Table 4 change of NO_X of major industries

	TE	PE	CE	coal	oil gas	petrol	coking	Gas
Top 5 decreasing inds								
elecsteam	-173.83	-0.13	-173.70	-168.63	-0.54	-4.40	-0.02	-0.12
basicchem	-0.37	-0.08	-0.30	-0.20	-0.01	-0.03	-0.06	0.00
ironsmelt	-0.30	-0.06	-0.24	-0.09	0.00	0.00	-0.15	0.00
brickmatel	-0.15	-0.09	-0.06	-0.05	0.00	-0.01	0.00	0.00
roadpasfreg	-0.07	0.00	-0.07	-0.00	0.00	-0.07	0.00	0.00
Top 5 increasing inds								
cement	1.17	-0.25	1.41	1.39	0.00	0.02	0.01	0.00
paperprod	0.64	0.00	0.64	0.61	0.00	0.03	0.00	0.00
cottonTextil	0.35	0.00	0.35	0.33	0.00	0.02	0.00	0.00
trade	0.20	0.00	0.20	0.09	0.00	0.10	0.00	0.01
otherProFood	0.18	0.00	0.18	0.15	0.00	0.03	0.00	0.00

Data Source: Simulation of CGE model.

Second, for the change of amplitude, compared with SO_2, NO_X emissions vary with smaller range. Except thermal power industry, changes in emissions of other industries are small. The NO_x emission of thermal power industry decreases by 174 ten thousand tons, and among other industries, except the cement manufacturing industry (12000 tons), no change is more than 10000 tons. We can see that other food processing industry which ranks as the fifth in the increasing emissions only increases by 1800 tons of NO_X emissions, and road transport industry which rows in the fifth in the decreasing emissions only drops by 700 tons.

Third, in terms of the energy products, emissions of NO_X and SO_2 from combustion are caused by different energy sources. This is because in the baseline emissions database, emissions of different energy products are different in its composition. Looking from the average of all industries, the proportions of NO_X

emissions from coal, oil gas, petrol and other energy products are 88%, 1%,7% and 4%, and the proportions of SO_2 are 58%, 24%, 13% and 5% accordingly. We can clearly see that, coal is the main source of these two pollutants. As for secondary sources, NO_X is derived from petrol combustion, and SO_2 is derived from oil gas.

5. Conclusion and Policy Suggestions

This study uses a CGE Model to simulate the impact of raising the emissions standard for thermal power plants on Chinese economy and air pollutants emissions. Our simulation results show that raising the emission regulation for thermal power plant will greatly reduce emissions of atmospheric pollutants. SO2 and NOX emissions decrease by 21.9% and 13.2%, respectively. But from an economic point of view, macro-economic cost is high. Calculation indicates that the new standard will lead to 1.33% decrease in China's GDP. If the GDP growth rate is calculated by 7.8% in 2012, the result is roughly equivalent to approximately 8 weeks' economic stagnation in China. From the price and the structure of domestic demand, the new standard will not push up the CPI; on the contrary, it will curb inflation and improve the structure of domestic demand. In terms of industrial output, thermal power industry output will fall by 4.37%. The new policy helps to reduce the output of high energy-consuming industries, boost the output of consumer goods industries and then reduce the emission of atmospheric pollutants. In addition, it also leads to increases in the private consumption and other labor-intensive industries outputs due to the decreased labor cost. Based on the simulation results, main policy recommendations are given below:

(1) The emission reduction policy for thermal power industry should be implemented step by step. The simulation results show that the impact of the new standard on GDP is large, therefore, when the government formulates and implements

emission reduction policies, the stability of economy should be considered. Economic development and environmental governance should be complement with each other. We should not sacrifice the economic development in order to achieve the emission reduction targets within a short period of time.

(2) More investments should be put into equipments for energy conservation. The implementation of the new regulation will improve the development of related energy conservation technology and market with a new hundred-billion-Yuan market of equipments for eliminating sulfur dioxide (SO2) and nitric oxide (NOX). The government should enhance foreign technology transfer (inflow) and help domestic firms' innovation activities, striving to make these industries take the leadership in a new growth area which connects to the green economy and sustainable development.

(3) The industrial structure of thermal power industry should be adjusted. Thermal power industry is a major source of air pollutants like SO2 and NOX. In the long term, the thermal power industry should gradually change the current dependency on coal, substituting the energy input from non-renewables to renewables like hydro and wind power. In the short term, the thermal power industry should strengthen the monitoring and management of exhaust gas, increase energy-saving emissions reduction technology research and development, shifting from "terminal management" to process-based emissions reduction.

References

[1]. The Standards of Air Pollutant Control for Power Plants Manual (the Second Draft), Chinese Research Academy of Environmental Sciences and State Power Environmental Protection Research Institute(in Chinese).

[2]. Zhong Xiang Zhang, Can China afford to commit itself an emissions cap: An economic and political analysis, Energy Economics 22 _2000. 587]614.

[3]. Russell Pittman&VanessaYanhua Zhang, Electricity Restructuring in China: How Competitive will Generation Markets Be? The Singapore Economic Review, Vol. 55, No. 2 (2010) 377–400.

[4]. Dallas Burtraw et al, Economics of Pollution Trading for SO2 and NOX, Resources for the Future, 2005(3).

[5]. SUN,S.(2001). Application of Engineering Economic Analysis in the Making of Pollutant Discharge Standards and the Determination of Pollution Control (in Chinese). *Urban Environment & Urban Ecology*, 14 (06), 14-15+33.

[6]. SHANG, J.C., ZHANG,L.Q.(2007). Research and Application of Technologies in Energy-Saving, Emission-Reducing and Optimal Resource Allocation of Electric Power System(in Chinese).*Power System Technology*, 31(22),58-63.

[7]. JING, P., YUE,T., LI,X.Y., GAO,X.J., ZHANG,Y.C.(2009). Control Standards, Policy Analysis and Research on Nitrogen Oxides in Thermal Power Plants (in Chinese).*Research Progress*, 04:19-23.

[8]. SUN, W.M., ZHANG,J.(2012). Discussion on Power Generation Company's Countermeasures to New Emission Standard of Air Pollutants(in Chinese). *Electric Power Environmental Protection*, 28(01),12-14.

[9]. FU,R.(2011). Technical and Economic Analysis on the New Emission Standard of Air Pollutants for Thermal Power Plants(in Chinese). *Energy Technology and Economics*, 23(12),56-60+65.

[10]. QIN,Z.(2014). Technical and Economic Analysis on the Power Plant Denitration Project(in Chinese).*Manager' Journal*, 02:387.

[11]. WANG,S.(2005). The Influence and Countermeasure on the Thermal Power Plants of China GuoDian Group From the Atmospheric Pollutant Emission Standard(in Chinese). *NanJing University of Information Science & Technology*.

[12]. WANG,Z.S.(2013). Numerical Simulation on Effect of Coal-fired power Plants and Industrial Boilers and Motor Vehicle Source Pollutants Emission Standards(in Chinese). *Chinese Research Academy of Environmental Sciences*.

[13]. WANG, Z. (2013). Research on China’s power industry emissions of sulfur dioxide control mode under the new standard conditions (in Chinese).*Central South University*.

[14]. LIU, Z. Q. (2008). Study on the Estimation of NOx Emission from Thermal Power Industry in China(in Chinese). *North China Electric Power University*.

[15]. SHENG,Q.(2011). The Study on Emission Standards for Main Sources of NOx and Simulation of Their Environmental Impact (in Chinese).*Chinese Research Academy of Environmental Sciences*.

[16]. LIN,B.Q, LIU,X.Y., ZOU,C.Y., LIU,X.(2012). Resource Tax Reform: A Case Study of Coal from the Perspective of Resource Economics Social Sciences in China(in Chinese). *Social Sciences in China*,02:58-78+206.

[17]. J.Xie,S.Saltzman(2000). Environmental policy analysis: An Environmental Computable General Equilibrium Approach for Developing Countries.*Journal of Policy Modeling*,04:453-489.

[18]. Dixon P.B, Rimmer M.(2002). Dynamic General Equilibrium Modeling For Forecasting And Policy: A Practical Guide and Documentation Of MONASH.

[19]. Xu Y and Masui T, Local air pollutant emission reduction and ancillary carbon benefits of SO2 control policies: Application of AIM/CGE model to China. European Journal of Operational Research 198:315-325 (2009).

[20]. Y.X.He, S.L.Zhang,et al, Economic analysis of coal price-electricity price adjustment in China based on the CGE model, Energy Policy, 38(2010)6629-6637.

[21]. Dixon P.B, Rimmer M., Dynamic General Equilibrium Modeling for Forecasting and Policy. A Practical Guide and Documentation of MONASH, 2002.

[22]. Jean-Marc Burniaux&Truong Truong, " GTAP-E: An Energy-Environmental Version of the GTAP Model " https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=923

Chapter 7

Input–Output-Based Genuine Value Added and Genuine Productivity in China's Industrial Sectors (1995-2010)

Yuning Gao[1], Yunfeng Zheng[1], Angang Hu[1]

(1: School of Public Policy and Management, Tsinghua University)

Abstract: The rapid growth of China's economy has brought about huge losses of natural capital in the form of natural resource depletion and damages from carbon emissions. This paper recalculates value added, capital formation, capital stock, and related multifactor productivity in China's industrial sectors by further developing the genuine savings method of the World Bank. The sector-level natural capital loss was calculated using China's official input–output table and their extensions for tracing final consumers. The capital output elasticity in the productivity estimation was adjusted based on these tables. The results show that although the loss of natural capital in China's industrial sectors in terms of value added has slowed, the impacts on their productivity during the past decades is still quite clear.

Keywords: Genuine savings method, Total factor productivity, Input–output method, China

Acknowledgement: This study was funded by the CIDEG-IDE/JETRO-USITC-IGLCE joint research project "Tracing China's CO2 Emissions in Global Value Chains". We are grateful to IDE-JETRO for providing the opportunity to conduct this joint research in 2014. In addition, we thank Dr. Masami ISHIDA (Director-General, Development Studies Center, IDE-JETRO) for his helpful comments on this paper.

1. Introduction to “Green National Accounting”

The current system of national accounts based on nominal GDP is seriously flawed, as it does not deduct the loss of natural assets from the value added created through excessive exploitation of resources and energy. This exaggerates economic benefits by neglecting the costs associated with the rapid depletion of resources and serious environmental degradation, which can result in a reduction in real national welfare. In response, many scholars and abroad have argued for “green” GDP, which considers environmental factors in the system of national accounts. Deducting from GDP the value of depleted natural resources, the costs of ecological degradation and the costs of restoring natural resources and the environment more comprehensively reflects changes in the environmental economy. This effort began with measuring net welfare as part of traditional GDP accounting (Nordhaus and Torbin, 1972; Samuelson and Nordhaus, 1992) as follows:

Net National Products (**NNP**) = GNP - Consumption of Fixed Capital (1)

The most systematic way to calculate the quantitative costs of resource consumption and pollution release is green national accounting. Since the 1990s, the UN Statistics Division, the UN Environment Programme, the World Bank, and other international institutions have worked together to study the definition of environmental accounting. This work led to the release in 1994 of the System of Integrated Environmental and Economic Accounting (SEEA). With development of the research and practice of integrated economic and environmental accounting, SEEA 2000 was released in June 2001 after discussion and revision, laying out steps to implement a system of integrated economic and environmental accounting. After much revision, SEEA 2003 was released (UN et al., 2003). Through efforts spanning the past 10 years, the SEEA Central Framework (UN et al., 2014) has become the international standard of the UN Statistical Commission and is now internationally recognized as the statistical framework of environmental and economic accounting.

The SEEA system proposes the concept of environmentally adjusted domestic product (EDP) based on nominal GDP which is the balance of conventional GDP after deducting costs of resource depletion and environmental degradation. Today this is what we call green GDP. Green GDP can be understood as GDP obtained using the System of National Accounts (SNA) after considering external factors and natural resources to more comprehensively reflect the economic welfare of a nation or region. SEEA amends the traditional SNA after considering the economic impact of non-productive natural assets and the environment. In matrix national accounting, the environmental and economic costs of using non-productive resources and releasing pollution should be added into the input, while the benefits of resource restoration and pollution treatment should be added into the output.

Net Domestic Product (**NDP**) = GDP – Resource and Environmental Degradation (2)

The social accounting matrix including resources and the environment by Atkinson and Hamilton and Pearce (1997) focuses on resource depletion and carbon emissions without considering the costs of emitting other pollutants. By combining a theoretical framework for accounting that systematically traces the generation and distribution of value added with green national accounting, we can obtain green national accounting under open conditions. In a social accounting matrix that incorporates resource and environmental factors into net national product (GDP minus productive fixed-asset depreciation that includes foreign savings rate), we can obtain the net resource product

(NRP) after deducting resource depletion (nR-ng) from net national product. Similarly, we deduct environmental emission losses ($\sigma e-\sigma d$) and can obtain net environment product (NEP).

Table1 Social Matrix Including Resources and Environment

DISPOSITION

SUP

	Production	Factors	Institutions	Saving	RoW	Resources	Environment	**Totals**
Production			C	I	X			Total disposition of goods and services
Factors	NDP							Net disposition of goods and services
Institutions		NDP				NRP	NEP	Disposition of welfare
Saving	δK		S_g			n.R	$\sigma.e$	Tot. disposition of saving (investment finance)
Rest of World	M			(X-M)				Total disposition to rest of world
Resources				n.g				Gross Resource Product
Environment			$P_B.B$	$\sigma.d$				Gross Environmental Product

Totals	Total supply of human-made goods and services	Net supply of human- made goods and services	Supply of welfare (MEW)	Total supply of saving	Total supply to rest of world	Total supply of resources	Total supply of environmental benefits

Source: Atkinson, Hamilton and Pearce et al. (1997)

In 1995, the World Bank began to redefine and re-measure national wealth using genuine national accounting, which is based on their social accounting matrix framework. The formal model of genuine savings is given by Kunte et al. (1998) and Hamilton and Clemens (1998). Compared with systematic green national accounting, the genuine savings accounting and simplified adjusted net savings designed by the World Bank are more practical:

$$G=GNP-C-\delta K-n(R-g)-\sigma(e-d)+m \qquad (3)$$

Here, GNP is gross national product, C is consumption, δK is the depreciation rate of produced assets, n is net marginal resource rental rate, g is the amount of growth of resource stocks, R is the amount of depletion of resource stocks, σ is marginal social cost of pollution, e is the amount of growth of the stock of environment benefits, d is the quantity of natural dissipation of the pollution stock, and m is investment in human capital (which is measured with current education expenditures, does not depreciate, and can be considered as a form of disembodied knowledge).

Furthermore, GNP-C is traditional gross savings, which includes foreign savings; GNP-C-δK is traditional net savings; -n(R-g) is resource depletion; -(R-g) is the change in resource stocks (which are assumed to be costless to produce); -σ(e-d) is pollution emission costs; and -(e-d) is the change in pollutant stock.

Natural resources depletion is measured using the rent gained from the exploitation and procurement of natural resources. This rent is the difference between the price of production calculated using the international price and total production costs. These costs include the depreciation of fixed capital and the return on capital. One thing to remember is that while the exploitation of natural resources is necessary for economic growth, if resource rents are too low it can lead to over-exploitation. If the rents gained are not reinvested, but rather used for consumption, it is also “irrational”. Pollution loss here mostly refers to CO_2 pollution. This is calculated using the global marginal loss caused by the emission of one ton of CO_2, which Fankhauser (1995) suggested was 20 US dollars.

It should be noted that in China, this work is still in its infancy, due to the absence of an enabling environment and numerous other difficulties. For example, in resource and environmental accounting, we consider physical quantity accounting for only four natural resources: land, forests, underground mineral resources, and water. Much fundamental work is just beginning, including theoretical research, the design of the integrated framework, formulation of an accounting plan, the establishment of implementation steps, and pilot programs. We are still far from the basic requirements of SEEA. For instance, one key problem in the consideration of resources and the environment in a system of national accounts is how to value these resources and the environment. This requires us to understand more than just the quantitative value of resource consumption and the cost of emitting pollutants. Without a clear understanding of real resource consumption and the amount of pollution in different regions and industries, we are unable to accurately calculate their quantitative value.

Some Chinese scholars (e.g., Lei, 2000, 2011; Liao, 2005, 2012) have attempted to establish green national accounting in China and to build a green input–output table and green society accounting matrix of selected years between 1992 and 2002. Because of limited access to data for the time period, related research efforts all strong assumptions in the physical quantity accounting of resource depletion and pollution release. The green GDP compiled by China’s environmental protection agencies in 2004 mainly considered the cost of releasing pollution, not the loss brought about by the consumption of resources, especially non-productive ones. Hu (2001, 2005, 2013) extended the definition given by the World Bank in order to calculate China's green savings rate.

2. Indirect Decomposition at the Sector Level

When we examine natural capital at the sector level in China, the estimation of the rental rate for the natural resources of each sector will become difficult because of the lack of price data. To simplify the accounting, we assume that the total production costs (including the depreciation of fixed capital and return of capital) per unit of the natural resource used is equal across the provinces in a given year. A consequence of this assumption is that the rental rate per unit of the natural resource is also equal across the provinces, since the production price (the international price) is the same. Energy depletion is defined as the product of unit resource rents and the physical quantities of energy extracted. We can therefore calculate the energy depletion of sector i :

$$D_i^E = n_i E_i^E = nE_i^E = \frac{D^E}{E^E} E_i^E = D^E \frac{E_i^E}{E^E} \qquad (n_i = n_j = n) \qquad (4)$$

This shows that the share of the total energy depletion of a sector is actually weighted by its energy extraction share. Here D^E refers to the energy depletion of China as taken from the World Development Indicator Database while E^E refers to the energy extracted (consumption) for China, which can be found in the China Statistical Yearbooks. The energy extracted for each sector E_i^E is taken from the *China Compendium of Statistics 1949-2009* (NBS, 2010) and *China Energy Statistical Yearbook* (NBS and NDRC, various years).

The difficulty in estimating CO_2 Damage is a result of the lack of CO_2 emissions data in any environmental statistics and materials for China. Because CO_2 emissions are of great importance and highly correlated with energy consumption, we must estimate the volume of CO_2 emissions by sector ourselves. We estimate CO_2 emissions using energy consumption according to the following formula:

CO_2 Emission = Consumption of Fossil Fuel [1] × Carbon Emission Factor × Fraction of Carbon Oxidized + Production of Cement × Processing Emission Factor

The Fraction of Carbon Oxidized refers to the physical amount of CO_2 released per unit of pure carbon gasified which is a constant of 3.67 (44/12). The most important coefficient here is the Carbon Emission Factor, which refers to the equivalent carbon emissions in the consumption of fossil fuel. The most commonly used factors are the one from the Energy Research Institute of China's National Development and Reform Committee, which is 0.67, the one from the Carbon Dioxide Information Analysis Center of the US Department of Energy, which is 0.68, and the one from the Institute of Energy Economics of Japan, which is 0.69. We use the first one. In addition, the production of cement will emit more CO_2 than the consumption of fossil fuels because of the calcination of limestone, producing on average 0.365 tons of CO_2 per ton of cement (China Cement Net, 2007).

In this paper, data on energy consumption structure, total energy consumption of 1978-1994 and cement production are from *China Compendium of Statistics 1949-2009* (NBS, 2010), while data on provincial aggregate energy consumption for 1995-2008 are from the China Energy Statistical Yearbook (NBS and NDRC, various years).

The estimation of mineral depletion is slightly more complicated. This is defined as "the product of unit resource rents and the physical quantities of minerals extracted

---

[1] More accurate calculations should exclude the carbon stored. Here we use the approximate amount because of limited data.

(specifically, bauxite, copper, iron, lead, nickel, phosphate, tin, zinc, gold, and silver). We exclude two of those minerals, gold and silver, due to a lack of production data. The assumption of one price in total production costs is also used here so we can write the mineral depletion of the province *i* as follows:

$$D_i^M = n_i E_i^M = n_i^I E_i^I + n_i^P E_i^P = n^I E_i^I + n^P E_i^P = n^M \left(\frac{n^I}{n^M} E_i^I + \frac{n^P}{n^M} E_i^P\right)$$

$$= \frac{D^M}{E^M}\left(\frac{n^I}{n^M} E_i^I + \frac{n^P}{n^M} E_i^P\right) = D^M \frac{w_1 E_i^I + w_2 E_i^P}{w_1 E^I + w_2 E^P} \qquad \left(w_1 = \frac{n^I}{n^M}, w_2 = \frac{n^P}{n^M}\right) \qquad (5)$$

Here n^M and E^M refer to the rental rate and extraction of minerals and I and P those costs for iron and phosphate. We are restricted to using only the international prices found in *World Bank Commodity Price Data* as weights for the eight mineral resources due to the unavailability of data on their domestic prices. According to the World Bank definition, a country’s natural capital is lost in only the domestic production of fossil fuels, ores, and so forth

The decomposition of natural capital lost *D* therefore occurs on only the block of intermediate inputs and final use in the input–output table. The intermediate “use” of the natural capital lost will be decomposed and re-combined into the real “use” for the first step as follows:

$$D_{out} = A^T D + CD = (A^T + C)D \qquad (6)$$

Here D is a 1 × n vector of the natural capital lost in the sector. A^T is the transpose of the direct input coefficient matrix, and C is a diagonal matrix of the ratio of final use in the total of intermediate inputs and final use.

$$C = diag(1 - \textstyle\sum_i a_{ji}) \qquad (7)$$

As these are total input coefficients in the general input–output models, here they must also incorporate the indirect loss of natural capital through the cycling of intermediate goods. Therefore, the final decomposition of the initial natural capital loss is similar to the derivatives of the Leontief inverse and should be written as follows

$$D'_{\text{out}} = CD + CA^T D + CA^T A^T D + \cdots = C(I - A^T)^{-1} D \tag{8}$$

In the calculation of the data for this paper, the decomposition of the natural capital loss in a sector must first add up the totals for each of the 36 industries[1] by sector according to the classification of the input–output tables and then be divided again after transformation. Therefore, the decomposition is based on the input–output table of the adjacent year of the data (see Table 2).

Table 2 Years Covered in Input–Output Tables

Based input-output table	Number of total sectors	Year covered
1995 extended input-output table	33	1994、1995
1997 input-output table	40	1996、1997、1998
2000 extended input-output table	40	1999、2000
2002 input-output table	42	2001、2002、2003
2005 extended input-output table	33	2004、2005
2007 input-output table	42	2006、2007、2008
2010 extended input-output table	65	2009、2010

Although most energy depletion and all mineral depletion were counted in the consumption of industrial sectors, this decomposition shows that around half of the natural capital loss was finally used by other non-industrial sectors such as construction and transportation. Compared with the unadjusted natural capital lost, the ratio of

---

[1] Mining of Other Ores before 2003, Manufacture of Artwork and Other Manufacturing, and Recycling and Disposal of Waste after 2004 were classified as other due to the lack of a continuous series.

adjusted loss to gross value added was about 3% to 8% lower, showing a more stable proportion to the total value added of all industrial sectors.

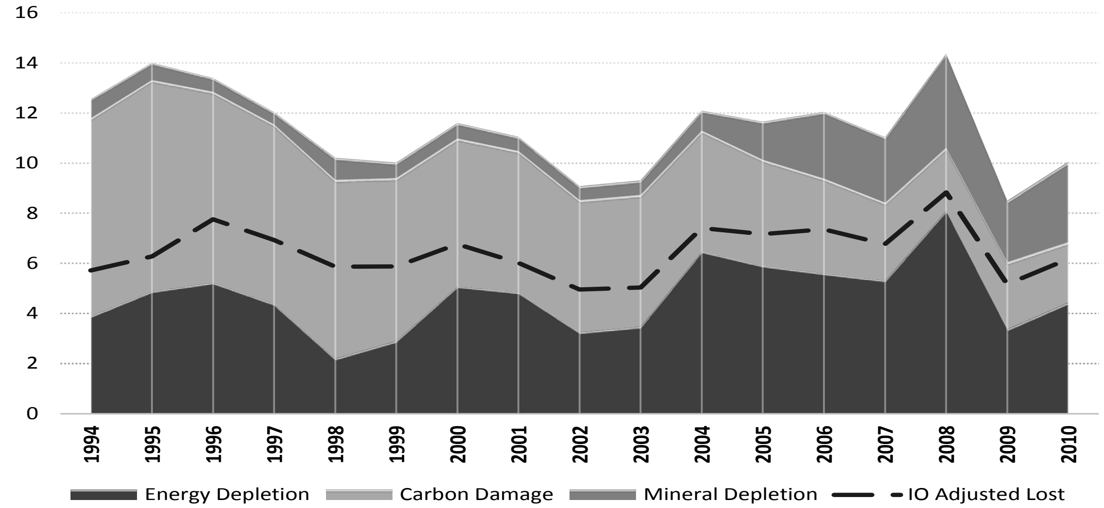


Figure 1 Natural Capital Lost as of Industrial Value Added

3. Genuine Investment and Genuine Capital Stock

(1) Industrial Genuine Value Added

The accounting of the industrial genuine value added uses the same method as the genuine savings rate. With the exception of the Production and Supply of Gas sector, the sector with the lowest share of genuine value added fluctuated between 80% and 85% of traditional value added with a peak of 88.7% in 2004. Before the year 2000, genuine value added in the Production and Supply of Gas sector was always lower than that in the others, especially in 1999 when genuine value was only 71.44% of its value added. This is mainly because of the high energy depletion and comparatively low value added in this sector in the late 1990s.

The sectors with the highest share of genuine value added were usually the Petroleum and Natural Gas and Tobacco sectors. These sectors maintained more than 99% of their traditional GDP. Overall the average share of genuine value added in all sectors rose from 92.7% in 1995 to 96.3% in 2010.

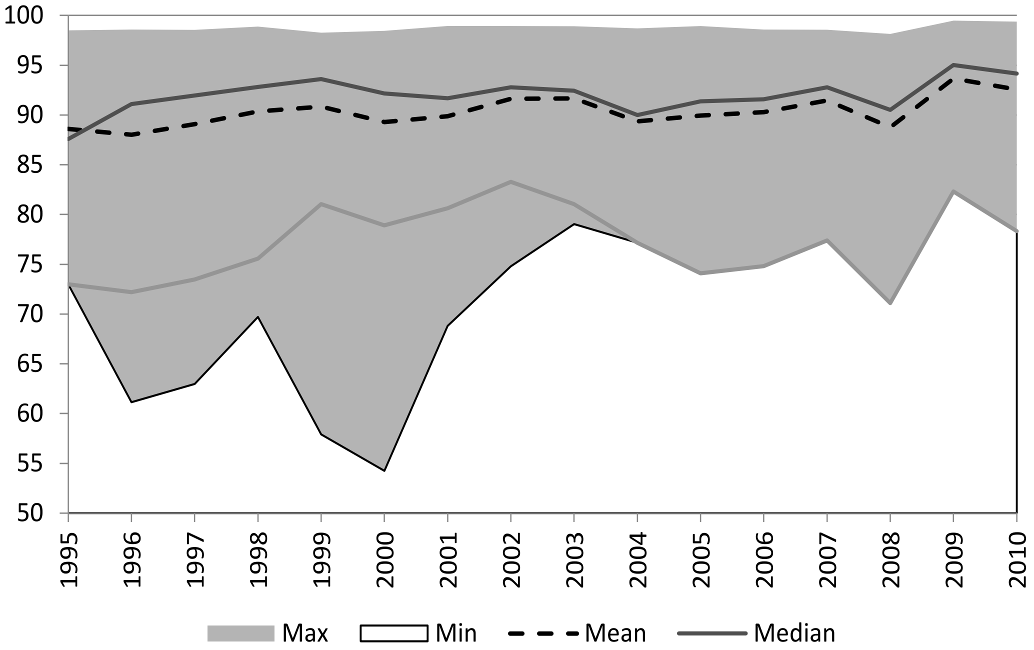


Figure 2 Share of Genuine Value Added as Traditional Value Added

(2) Industrial Genuine Investment

According to formula (1), we can define the genuine investment of sector *i*:

$$I'_t = I_t - n_i (R_t - g_i) - \sigma_t (e_t - d_t) + m_i \qquad (9)$$

I_{it} is traditional investment, $n_{it} (R_{it} - g_{it}) - \sigma_{it} (e_{it} - d_{it})$ is the natural capital lost, and m_{it} is education expenditure. The data on investment come from various years of the China Statistical Yearbook. From the accounting data of industrial firms, we chart the changes in the original value of fixed assets to form a continuous series of fixed capital formation under the expenditure approach. However, because of the limited availability of data, the deflator for fixed capital formation must use the price index for China’s overall fixed asset investment, which is identical across sectors.

The average of the traditional fixed capital formation ratio of the industrial sectors varied between 16% and 30%. While, the genuine fixed capital formation rate showed greater fluctuation with highs of more than 25% and lows of about 7%. The genuine fixed capital formation rate was lower than the traditional one because the deduction of natural capital lost on capital formation would be more obvious than value added.

However, the impact of natural capital loss on genuine fixed capital formation and genuine value added appear to be different, so the non-input–output adjusted genuine fixed capital formation ratio is higher than the adjusted series. The 2004 peak is a result of adjustments to performance indicators in the National Statistic Bureau’s first Economic Survey of China. Because of the lack of suitable benchmark data, we cannot isolate this effect and adjust our own calculations.

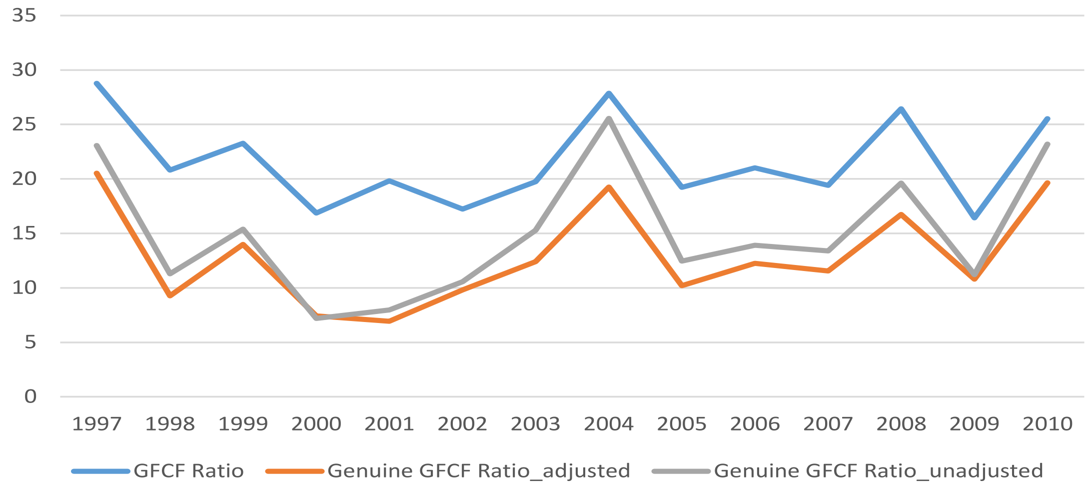


Figure 3 Average Traditional / Genuine Fixed Capital Formation Ratio

Notes: Utility sectors excluded.

(3) Industrial Genuine Capital Stock

In using the perpetual inventory method to measure productivity, the difference in capital formation greatly influences the capital stock. We can define the genuine capital stock as the following:

$$K'_{it} = K'_{it-1}(1-\delta_{it}) + I'_{it} \quad (10)$$

Here, δ_{it} is the depreciation ratio, that is, the ratio of capital depreciation to the original value of fixed assets. In the accounting data of industrial firms, the change in accumulated depreciation (gap between the original value of fixed assets and net value of fixed assets) provides a series of capital depreciation. I'_{it} is the Genuine Fixed Capital Formation.

The capital stock in 1994 for each sector is shown here as their net value of fixed assets as a constant price in the year 2000. genuine capital stock in fact begins in 1995 because of limited data on genuine fixed capital formation. The accumulation of natural resource depletion and environmental damage leads to a decline in genuine capital stock relative to traditional capital stock. The trend reversed after the 2007–2009 global financial crisis, meaning that the growth rate of genuine capital stock has surpassed that of traditional capital stock. Before 2006 the Metal Products sector had the lowest capital stock while the Electrical Machinery and Equipment sector had the next lowest. Both of these sectors suffered because of their heavy use of non-ferrous metals.

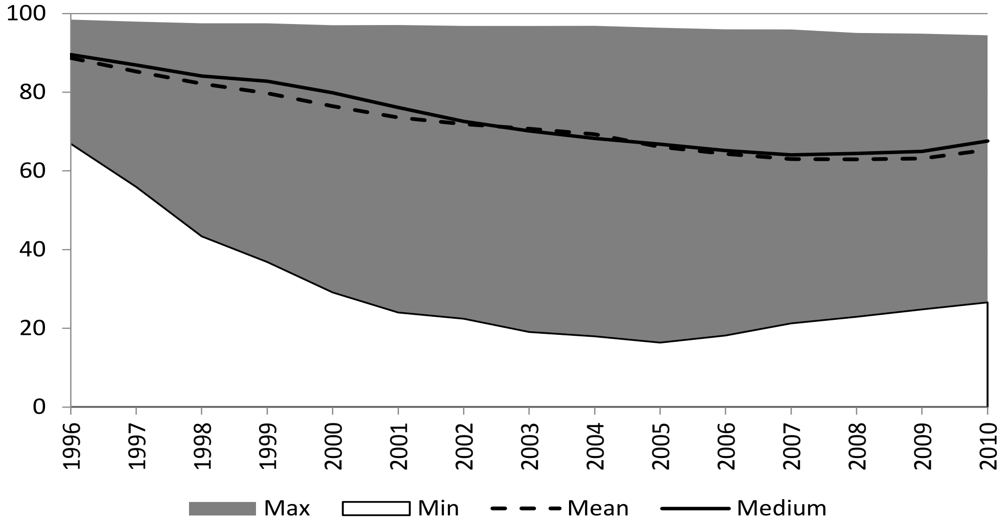


Figure 4 Share of Genuine Capital Stock as a Portion of Traditional Capital Stock

4. Accounting Genuine Productivity

Growth accounting is considered to be the classic method of productivity analysis. Assuming constant returns to scale, we can decompose GDP growth into factor contribution and productivity contribution. The coefficients of capital growth and labor growth, or their elasticity to output, were shown to be their proportion of GDP under the income approach. The new World Input Output Database also provides a complete series of industry-level capital / labor share. The adjustment on the value added will affect the operating surplus portion of capital compensation and therefore change the capital output elasticity:

$$\alpha' = \frac{\alpha-\rho}{1-\rho} \tag{11}$$

α is the original capital output elasticity

ρ is the proportion of natural resource depletion and environmental damage in original value added

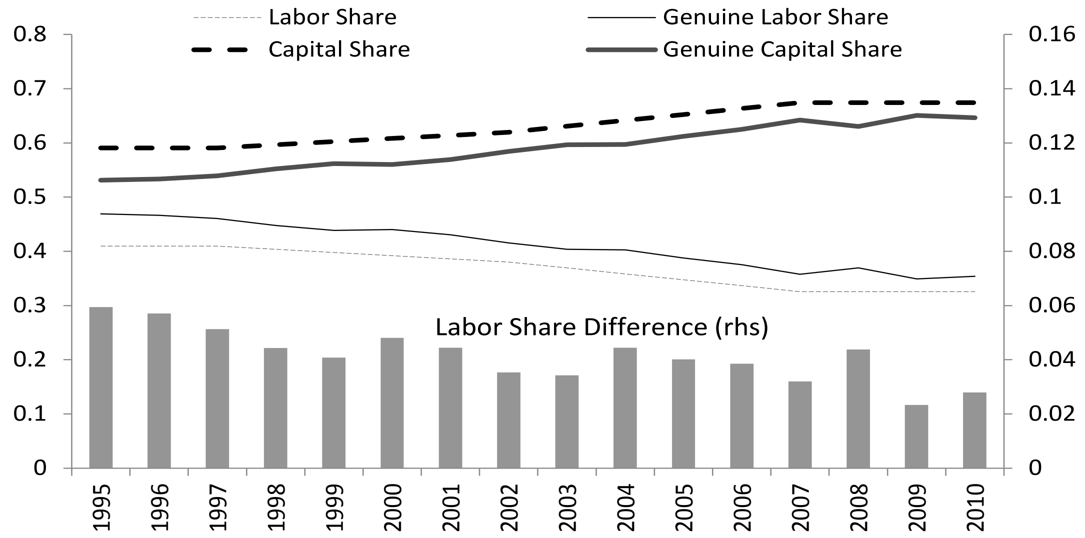


Figure 5 Genuine Labor / Capital Share

With the decline in overall labor share, the gap between traditional and genuine labor share narrowed from 0.06 to 0.02. This indicates a rise in the share of capital and a catching up in the genuine capital share. This gap comes from a loss of capital compensation from resource depletion and environmental damage, while the decrease in natural capital loss was the driving force behind this convergence.

Assuming constant returns to scale where the sum of labor output elasticity and capital output elasticity is equal to 1, the growth rate of genuine total factor productivity can be expressed in the widely used Divisia Productivity Index (Jorgenson and Griliches, 1971; Star and Hall, 1976) recommended by the OECD Productivity Handbook as follows:

$$\dot{A}' = \dot{Y}' - \alpha' \dot{K}' - (1 - \alpha') \dot{L} \qquad (12)$$

A’ is the genuine total factor productivity

Y’ is the genuine value added

K’ is the genuine capital stock

α’ Is the adjusted labor share

While keeping input factors and output measures in constant price, we see that the contribution of the growth of input factors to the output growth is the key measure in estimating different patterns of productivity. Although the level of genuine value added was lower than the traditional measure, the narrowing gap makes the growth rate of the former higher than the latter on average. The growth rate difference was just 0.4% during the first period between 1995 and 2002. This difference narrowed to 0.3% between 2003 and 2010.

The traditional measure of the growth of capital stock was much higher than the genuine measure because the accumulation effect of natural resource depletion and environmental damage seriously lowers the growth rate of capital stock in the genuine measure. This effect led to a 3% slowdown of genuine capital stock growth on average. This gap narrowed from 4.8% during the first period of time to 1% during the second period. This indicates that the traditional measure overestimates the contribution of capital stock in the total growth of China’s industrial sectors as the natural capital lost was still recorded as part of fixed capital formation. Therefore, under the traditional measure the total growth of capital stock contributed more than 60% of value added but 45% under the genuine measure, similar to the contribution of total factor productivity.

The most important part of growth accounting is total factor productivity. Here the growth rate was 2.5% higher under the genuine measure and its contribution to value added growth is 16% higher even considering that the value added growth was slightly higher. This new pattern fundamentally altered the traditional view that capital stock completely dominated the value added growth in China’s industrial sectors. Here we find that total factor productivity played a similar role. There is also a gap in the growth rate of total factor productivity of 3.7% between the two periods, making their contribution to value added growth close to each other, with both lower than one third under the traditional measure. In contrast, the total factor productivity growth rates between the two periods under the genuine measure have a gap of only 1.7%. This emphasizes that its contribution to average industrial value added growth between 1995 and 2002 was much higher at about 64%. This was even 11.5% higher than the average contribution of the growth capital stock. However, this intensive growth model was replaced by a more extensive one during the second period of time. Here total factor productivity growth contributes only around one-third of the genuine value added growth, and there is no obvious difference from the traditional measure.

Table 3 Growth Accounting of Genuine Value Added Growth

	Value added	Labor Growth	Capital Growth	TFP Growth
		Traditional Value Added Growth		
1995-2002	9.28	-2.01	13.44	2.69
		（-21.69）	（88.94）	(28.95)
2003-2010	20.89	2.81	14.87	6.37
		（13.44）	（47.04）	(30.47)
1995-2010	14.94	0.37	14.15	4.51
		（2.47）	（60.49）	(30.19)
		Genuine Value Added Growth		
1995-2002	9.69	-2.01	8.64	6.20
		（-20.77）	（52.36）	(63.92)
2003-2010	21.10	2.81	13.88	7.88
		（13.31）	（41.52）	(37.34)
1995-2010	15.26	0.37	11.23	7.03
		（2.41）	（45.24）	(46.11)

Notes: Numbers in brackets are contribution as a percentage. They do not add up to 100% as they are averaged over all items. TFP: total factor productivity.

In the detailed industrial sectors in particular we find that all of the total factor productivity growth gaps were positive, which means that they all achieved higher total factor productivity growth under the genuine measure. However, several sectors had lower genuine value added growth compared with the traditional measure. A general pattern is that the higher the value added gap (genuine measure minus traditional measure), the higher the total factor productivity gap. This pattern can be explained when we consider that the higher value growth rate comes mainly from the higher total factor productivity growth under the genuine measure, or that the genuine growth model was a more total factor productivity driven model.

The difference in the Electrical Machinery and Equipment manufacturing sector over the whole period from 1995 to 2010 was on top of the detailed industrial sectors, reaching 6.5% yearly. This was followed by the 5.6% found in the Non-ferrous Metals Manufacturing and the 4.7% in Metal Products Manufacturing. Among other heavy metal-consuming sectors, the General and Special Purpose Machinery Manufacturing and Ferrous Metals Manufacturing sectors showed the unique characteristics of having high total factor productivity gaps under lower genuine value added growth, meaning that the effects of mineral depletion damaged their output growth but left more room for extra total factor productivity growth under their accumulation in capital stock.

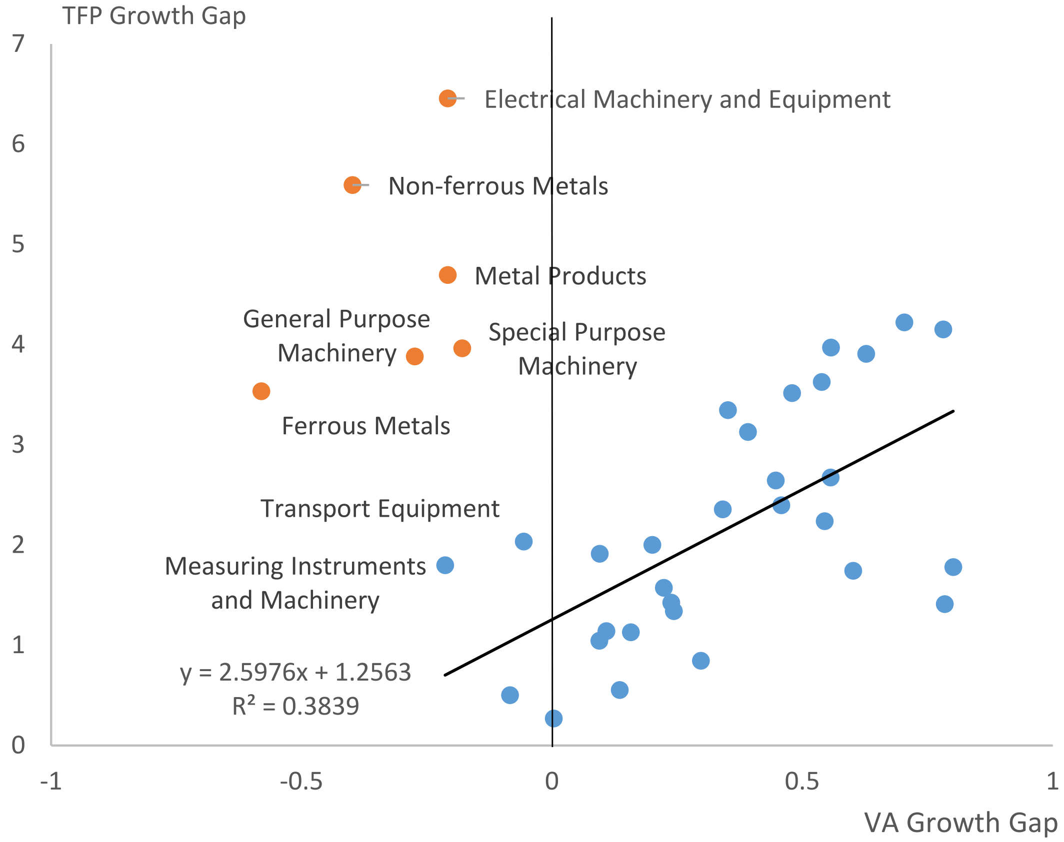


Figure 6 Traditional / Genuine Productivity Difference

5. Conclusion

The natural resource depletion and carbon damage cost nearly one tenth of China’s industrial gross value added. The loss to value added fluctuated between 10% in mid 1990s to 8.5% in 2010, while the accumulation effect that drove the loss in capital stock peaked in 2007 at 30% of capital stock on average. They also lead to an average 3% to 6% lower sector-level productivity growth under the traditional measure. However, the genuine measure showed that China’s industrial growth model was more productivity driven, especially during the period between 1995 and 2003. However, some heavy metal consumption sectors that showed lower genuine value added growth compared with the traditional measure achieved the highest genuine total factor productivity growth.

The over-consumption of natural resources and the related pollution will greatly discount the value added growth and capital stock of industrial sectors. Greater loss of natural capital will lower the genuine measure of value added compared with the traditional measure and will slow the accumulation of genuine capital stock. More intensive use of natural capital will speed up genuine capital stock growth. We believe that the intensive use of resources, the reduction of carbon, and new technology in resource consumption and emission control all contribute to industrial total factor productivity growth.

One policy implication is that the application of genuine GDP accounting at both the national and industrial levels can help governments to understand the importance of green growth and their environmental and resource constraints. This new measure provides an alternative way to understand the growth model of different industries and can help with the design of industrial policy by integrating the negative effects of environmental pollution and the overconsumption of non-renewable resources into the current national accounting system. This will then provide a new landscape for the structural transformation strategy of the Chinese government.

Furthermore, linking resource depletion and the environmental damage of various industries through an input–output system provides more comprehensive information about their generation and final consumption so that we can better understand the different levels of responsibility through the production chain. This may help policy makers to understand the systematic influence of a specific industrial policy and to break away from traditional GDP-oriented high-carbon, high-pollution development patterns toward a more comprehensive way of policy making.

One limitation of this study is that we focused on only physical capital loss without explicit consideration of human capital loss. As a possible extension, measuring the effects of environmental damage such as PM2.5 pollution on human health and human capital and then linking these effects to genuine productivity analysis would be a promising area of future research.

Reference

[1]. Atkinson, G., Dubourg, R., Hamilton, K., Munasinghe, M., Pearce, D., & Young, C. (1997). *Measuring sustainable development: macroeconomics and the environment*. Edward Elgar Publishing Ltd.

[2]. Fankhauser,S. ,*Valuing Climate Change :the Economics of the Greenhouse* . London: Earth scan, 1995.

[3]. Hamilton, Kirk and Michael Clemens, *Genuine Savings Rates in Developing Countries*, August, The Environment Department, The World Bank, 1998.

[4]. Hamilton, Kirk, Giovanni Ruta, and Liaila Tajibaeva. 2005. Capital Accumulation and Resource Depletion: A Hartwick Rule Counterfactual. World Bank Policy Research Working Paper No. 3480.

[5]. Jorgenson, Dale, and Z Griliches. “Divisia Index Numbers and Productivity Measurement.” *Review of Income and Wealth* 17, no. 2 (1971): 53-55.

[6]. Kunte, Arundhati , Kirk Hamilton, John Dixon and Michael Clemens, *“Estimating National Wealth: Methodology and Results”* January, The Environment Department, The World Bank, 1998.

[7]. Maler, K.-G., National Accounts and Environmental Resources, *Environmental and Resource Economics,* Issue1, pp.1--15, 1991.

[8]. National Bureau of Statistics (NBS), 2007, *Data of Gross Domestic Product of China (1952~2004)*, Beijing: China Statistics Press.

[9]. National Bureau of Statistics (NBS), 2010. *China compendium of statistics 1949-2009.* Beijing: China Statistics Press.

[10]. National Bureau of Statistics (NBS) and National Development and Reform Committee (NDRC), various years, *China Energy Statistical Yearbook*, Beijing: China Statistics Press.

[11]. Spencer Star and Robert E. Hall, “An Approximate Divisia Index of Total Factor Productivity”, *Econometrica*, Vol. 44, No. 2 (Mar., 1976), pp. 257-263

[12]. World Bank ,*Expanding the Measure of Wealth: Indicators of Environmentally Sustainable Development*, The Environment Department of World Bank, 1997.

[13]. United Nations, European Commission, International Monetary Fund, Organization for Economic Co-operation and Development, World Bank, Integrated Environmental and

[14]. *Economic Accounting 2003*, http://unstats.un.org/unsd/envAccounting/seea2003.pdf.

[15]. United Nations, European Commission, Food and Agriculture Organization of the United Nations, Organization for Economic Co-operation and Development, International Monetary Fund, World Bank, *System of Environmental-Economic Accounting 2012—Central Framework*, New York: United Nations, 2014.