Can Smart Policies Reconcile Singapore's Green Economy with Sand Imports from Southeast Asia?

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Abstract

This article tries to increase public awareness of a crucial but rarely discussed global challenge by introducing a novel economic analysis: drawing on insights from various disciplines, it studies policies regulating sand extraction and trade. While sand is essential for construction and land reclamation worldwide, its extraction causes severe ecological damage in oceans, in rivers and on beaches and thus has high social costs. To derive solutions to this paramount global challenge, this article focuses on sand exports from developing countries in Southeast Asian to Singapore as a prominent example. It evaluates output, export and import taxes as the means to reduce sand extraction and trade. To this end, it utilizes an Eaton and Kortum type trade model within a general equilibrium framework. Overall, an output tax can reduce sand extraction to a large extent, while the economic costs are small for Singapore and slightly positive for the Southeast Asian sand exporters. As a novel policy, the sand tax can be implemented as a Sand Extraction Allowances Trading Scheme *(SEATS)*. This policy can help sustainably balance Singapore's economic growth with Southeast Asia's economic development.

Significance

Despite the global importance of sand to construction and the severe ecological effects of sand extraction, this is the first article in the field of social sciences to study policy measures including a novel Sand Extraction Allowances Trading Scheme *(SEATS)* to reduce sand extraction and trade.

Keywords

Sand extraction, trade policy, Singapore, Eaton-Kortum trade model

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Introduction

Due to its impressive socioeconomic development, Singapore has become one of the richest countries in the world and the Southeast Asia's front-runner economy.[3] Singapore's government fosters the country's front-runner position by promoting high social and environmental standards.[4] Nonetheless, a crucial challenge has existed for decades but has received almost no attention from economists despite being closely related to international trade and economic policy: The amount of Singapore's available land is limited, which has resulted in skyrocketing housing and infrastructure construction as well as massive land reclamation. These measures require vast amounts of sand and gravel[5]. As Singapore's own sand deposits have been exploited a long time ago, it has become the world's top sand importer by purchasing sand from neighboring developing countries in Southeast Asia – with substantial consequences for these countries.[6]

Although sand extraction creates valuable revenues, its distributional and ecological effects on the exporting developing countries are often harmful. While the mining companies earn profits, the local population, ecosystems and biodiversity suffer from the destruction of the Mekong, other rivers, beaches and small islands in the South China Sea. In the absence of technological or economic alternatives, Singapore's economic growth inevitably depends on sand imports, despite sand export bans. Driven by Singapore's ongoing growth and plans for more intensive land use and further land reclamation,[7] this dilemma will likely be exacerbated in the future.

Hence, seeking an efficient, fair and implementable solution of this dilemma, this article studies the economic effects of market-based policy instruments – a tax on sand output (or, equivalently, a *Sand Extraction Allowances Trading Scheme, SEATS*) and export and import tariffs – as measures to internalize, or at least mitigate, the environmental and related social externalities[8] of sand mining. Although such policies have been implemented to reduce CO_2 and SO_2 emissions in the European Union and the United

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[3] In the year 2015, Singapore held the fifth position worldwide based on the gross national income at purchasing power parity according to the World Development Indicators, http://data.worldbank.org/data-catalog/world-development-indicators (accessed 02/2017).

[4] Singapore Ministry of National Development, http://app.mnd.gov.sg/publications/others (accessed 02/2017).

[5] Throughout the article, the term "sand" comprises both sand and gravel. The two materials differ from each other primarily in their grain size, with gravel consisting of larger mineral grains than those of sand (Wentworth, 1922).

[6] In 2015, Singapore was the biggest sand importer in the world according to UN Comtrade (2016); according to UNEP (2014), Singapore is the world's top sand consumer in per capita as well.

[7] Singapore Ministry of National Development, http://app.mnd.gov.sg/Publications/Other-Publications (accessed 02/2017).

[8] For instance, the ecosystem of the river is destroyed, and fishermen lose their livelihood.

States, their application to resource extraction is, to our knowledge, novel. A comparable tax on sand extraction and imports currently exists in the United Kingdom.[9]

In practice, unilateral sand export bans of Southeast Asian countries have not been successful in reducing the overall sand extraction because such bans shift sand sales to the domestic market and sand extraction to other countries. Therefore, we propose implementing the abovementioned policy instruments as unified multilateral policies. Our simulation results are in favor of the unified output tax or, equivalently, the unified sand price emerging from the *SEATS* because these policies avoid the shift of sand extraction and sales, create welfare gains for the Southeast Asian exporters and cause only a minor welfare loss for Singapore.

The article focuses on Singapore and its Southeast Asian neighbor countries as a prominent example. Sand extraction, however, is a paramount global challenge. According to the "Precautionary Principle" of the Rio Declaration, research into the economic, political, geographic and physical facets of sand mining is urgently required (Global Witness, 2010). Sand and gravel represent the most important solid extracted material in the world with an extraction rate by far exceeding the renewal rate (UNEP, 2014).[10] In addition to the essential importance to construction, sand is increasingly used to restore or extend shorelines while the ocean continuously erodes them. Unfortunately, natural sand supply by rivers to the oceans is increasingly hindered by dams. Thus, due to lack of suitable sand deposits[11], beaches, river and ocean beds are destroyed by legal and illegal sand extractors. Consequently, the economic policy solutions discussed in this article are of broad international and interdisciplinary relevance and can be transferred to other countries. Because of the lack of research in the economic (policy) domain, this article sets a starting point for further research and tries to increase awareness of this topic by scientists, policymakers and the public.

Background

Recent geographic studies of Southeast Asia's Mekong River and its delta provide evidence of geomorphic changes such as riverbed incision, subsidence and coastal erosion (Bravard et al., 2013; Brunier et al., 2014; Anthony et al., 2015). In addition to upstream trapping of sediment, particularly by hydropower dams, and changes in tropical cyclone climatology (Nguyen et al., 2015; Darby et al., 2016),

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[9] Government of the United Kingdom, https://www.gov.uk/green-taxes-and-reliefs/aggregates-levy (accessed 06/2018).

[10] According to UN Comtrade (2016), the net weight of sand imports by all countries in 2015 amounted to almost 100 million tones.

[11] Sand from deserts is not suitable for construction.

geographic studies identify sand mining as a major contributor to geomorphic changes. Similarly, maritime sand mining caused the decline of small islands in the South China Sea and Indonesia (Global Witness, 2010; UNEP, 2014).

Sand mining causes various detrimental environmental and socioeconomic effects. It harms vulnerable habitats and protected areas such as mangroves, seagrass beds and coral reefs (Global Witness, 2010). The conservation of such unique areas requires the prohibition of mining activities as well as strict local control and enforcement. The extension of prohibitive regulation to *all* areas beyond protected areas, however, is incompatible with rising sand demand. Nonetheless, detrimental effects of sand mining also occur outside protected areas (Kim et al., 2008; Global Witness, 2010; Padmalal and Maya, 2014; Ako et al., 2014; UNEP, 2014): water flows and marine currents can be changed; the benthic fauna is destroyed; fish and crab populations decline in rivers and the sea causing a loss of fishermen's livelihood; the pressure on endangered species increases with a negative impact on biodiversity; bridges, river embankments and coastal infrastructure can be damaged; flood regulation and protection are impeded, and the agricultural use of floodplains can be restrained; the water table can be lowered and water supply impeded; and recreational functions can be reduced.

Despite the recently growing number of sand mining studies in other scientific disciplines, the economic analysis of sand mining and trade is, to our knowledge, limited to two working papers. Hoogmartens et al. (2014) examine sand extraction in Flanders based on a one-sector *Hotelling*-type growth model with resource extraction. The researchers estimate that the taxation of construction and sand extraction would extend the time frame until sand's depletion from 30 to over 40 years. Franke (2014) presents a narrative based on the *world-systems theory* to discuss the core-periphery structure of Singapore and its surrounding Southeast Asian countries focusing on sand trade. The author argues that Singapore has grown at the expense of its periphery while export bans in Southeast Asian countries have been undermined by illegal sand trade.

Policy

The following analysis examines a cost-efficient implementation of given targets for the allowed extent of sand mining (outside protected areas). To this end, it evaluates various market-based policy instruments imposing a tax (or, equivalently, a price emerging from the *SEATS*) on sand output (sales of extracted sand) or sand trade (via import or export tariffs) in addition to the market price of sand. In practice, these instruments can be combined with a *certificate* guaranteeing that the traded sand was extracted outside protected areas. The increased gross price of sand is expected to reduce sand demand

and trade while making alternative materials (wood, steel, recycled materials, byproducts, new mixtures, etc.) and construction techniques using these materials more attractive compared to standard concrete building techniques (e.g., UNEP, 2014).[12]

Leaving aside, in this analysis, (changes in) the *damages* caused by sand mining, the imposed policy instruments create different welfare and distributional effects for consumers and producers in the exporting countries and in Singapore, the importing country. Hence, we search for a suitable policy solution that keeps welfare losses of exporters and the importer low and reduces the discrepancy between winners and losers of sand mining and the imposed policy. The current export bans do not generate official revenues but instead encourage smuggling and unofficial rent-seeking. The introduction of taxes or tariffs, on the contrary, would generate official state revenues that can be used for social or environmental purposes related to sand mining, particularly as a compensation to those whose welfare is reduced by sand mining.

In theory, a site-specific *Pigou* tax that internalizes the social (ecological) costs of each sand miner with a tax rate equal to the social marginal damage would be optimal. Damages are, however, unlikely to be restricted to the local surroundings of an extraction site. Instead, they affect the entire downstream river system or the coastal area around the extraction site. Thus, following the *Samuelson* rule, the socially optimal tax rate should reflect the sum of *all* marginal damages for which the producer is responsible. Because the Mekong flows through several countries, damages are transboundary, i.e., the creators of and the sufferers from the externality are not located within the same jurisdiction. This complicates the policy implementation. Indeed, history has shown that uncoordinated regulation of sand mining by single Southeast Asian governments results in a shift of sand mining to other countries. Thus, a harmonized transboundary policy solution with a uniform tax rate including all relevant exporters and importers is recommendable as a practical solution (cf. the call for an international framework by UNEP, 2014) and will be used in this analysis. As in the climate policy case, this approach implies that the same total transboundary marginal damage is attributed to all Southeast Asian sand miners[13], resulting in an economically efficient solution.

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[12] In the model, the substitution effects are represented in an abstract (aggregate) way without an explicit representation of specific materials, techniques or research and development.

[13] In the model, there is one representative sand miner (i.e., sand sector) per region.

Methodology

For the economic policy analysis, we set up a global Eaton and Kortum (2002) type general equilibrium model of international trade with Ricardian specialization similar to that of Caliendo and Parro (2015) and nested constant elasticity of substitution (CES) production and consumption functions (see figures A1 and A2 and table A3 in the Appendix) similar to Pothen and Hübler (2018). This model type enables the explicit theory-based representation of international trade. In contrast to Pothen and Hübler (2018), the model equations are expressed as changes between a counterfactual and the baseline (see Dekle et al., 2008). Trade flows are determined by international differentials of fundamental productivity and input costs as well as trade costs. Unlike *Armington* trade models, the *Eaton and Kortum* model assumes neither home bias nor regional preferences. Instead, Ricardian specialization creates productivity gains via the endogenous choice of the lowest-cost varieties of each good (sector). Existing sand trade policies (export bans) are eliminated from the benchmark data based on an econometric estimation before imposing the policies being analyzed (see Section 4.4 of the Appendix). The model is formulated as a Mixed Complementarity Problem (MCP) with market clearance, zero-profit and income balance conditions as well as specific equations defining international trade and sand policies. The supplementary Appendix provides more information about the model, including mathematical details in Section 5.

Scenarios

We focus on the sand trade of the Southeast Asian exporters, *Cambodia (KHM), Malaysia (MYS), Myanmar (MMR), the Philippines (PHL)* and *Vietnam (VNM)*, with the importer, *Singapore (SGP)*[14], based on the GTAP[15] 9 dataset for the benchmark year 2011 as well as the UN Comtrade (2016) data. Figure D1 in the Appendix illustrates Singapore's sand imports according to official statistics. Because sand is not explicitly represented in the available global datasets, we disaggregate sand extraction from the remaining mining sector in the exporter countries. Similarly, we disaggregate sand as an input to

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[14] Instead of being exported to Singapore, the extracted sand can be sold in the same country or exported to the remaining Southeast Asian exporters (*KHM*, *MYS*, *MMR*, *PHL* and *VNM*; see table A5 in the Appendix). Sand exports to other countries and sand imports from other countries to *SGP* are negligible and are left out.

[15] The Global Trade Analysis Project data can be purchased at https://www.gtap.agecon.purdue.edu/default.asp. Additionally, 16 countries/regions of the world and corresponding trade connections (except sand) are represented by the model but not specifically analyzed (see table A1 in the Appendix). The model incorporates 15 production sectors and the investment good sector and the corresponding input-output connections with each other and with final consumption (see table A2 in the Appendix). There are two production factors, capital (including natural resources) and labor, with fixed region-specific endowments.

Singapore's production sectors and (private and public) consumption. The disaggregation procedure and the calibration to data are explained in Section 4.2 of the Appendix.

All types of taxation analyzed in the following policy scenarios implement a sand tax at a rate that reflects the actual physical sand content such that the damages created by sand extraction are proportional to the amount of extracted sand (for implementation details, see Section 4.5 of the Appendix). The sand tax can be interpreted as the market price emerging from a S*and Extraction Allowances Trading Scheme (SEATS)* with a fixed total amount of extracted sand (the "cap and trade" scheme). Although emissions trading schemes have been successful in tackling CO_2 and SO_2 emissions (Montgomery, 1972; Chan et al., 2012), the application to resource extraction is, to our knowledge, novel.

In the first policy scenario denoted by OutTax, we examine a sand output tax suggested by Kim et al. (2008), Hoogmartens et al. (2014) and UNEP (2014). The tax is imposed on the sales of extracted sand. The tax rates are internationally harmonized across exporters. In this scenario, the tax is imposed on the total sand extraction, regardless of whether the sand is sold in the domestic market or exported to Singapore. The tax revenues accrue to the representative consumer of the corresponding country as a lump-sum.

In the second policy scenario denoted by ExpTax, we study a uniform sand export tax (tariff) imposed by the Southeast Asian exporting countries. Similar to the OutTax scenario, this scenario requires an internationally coordinated policy solution. In contrast to the tax scenario, only the exported part of extracted sand is taxed and generates revenues for the representative consumer of the exporting country. The tax rate is internationally harmonized and reflects the actual sand content, as argued above. In this respect, this policy mimics the *border carbon adjustments* that have been studied in depth in the climate policy domain (e.g., Böhringer et al., 2012) and discussed controversially regarding the compliance with the World Trade Organization legislation.

In the third policy scenario denoted by ImpTax, we analyze an *import tax* (tariff) that Singapore's government imposes on sand imports from Southeast Asia. As before, the tax rate reflects the actual sand content. This policy scenario has the advantage that the Singaporean government can as a single actor decide on, implement and administer the import tariff in a unified way for all sand exporters without bargaining for an internationally coordinated solution. Unlike the previous two scenarios, the tariff revenues accrue to the Singaporean consumer (via the Singaporean government).

To evaluate the effectiveness of the three policy instruments, we vary the stringency of each instrument, i.e., the tax or tariff rate, and observe the impact on the amount of sand extraction and welfare of Singapore and the Southeast Asian sand exporters based on data for the benchmark year 2011.

According to the variation in the UN Comtrade (2016) data over time and considering Singapore's land reclamation plans, the actually traded and used sand volumes vary by a factor of 3.5 and can be expected to increase by up to a factor of seven in the future (for more details, see Section 4.3 of the Appendix). Hence, the alternative robustness check scenario HigDem will take this variation into account by imposing the policy instruments on an economy, in which Singapore's sand demand is assumed to rise fivefold as a realistic medium value.

Results

Figure D1 of the Appendix illustrates the quantity-based export shares of *SGP*'s trading partners in the model's benchmark year 2011 and their variation across other years according to the official UN Comtrade (2016) statistics. In 2011, *KHM* was the largest exporter (with a share of 62%), followed by *MMR* (28%). In what follows, let us refer to them as the *major exporters*. On the contrary, let us refer to the following countries as the *minor exporters*: *PHL* (9%), followed by *MYS* (1%) and *VNM* (close to 0%). Indonesia and other sand suppliers are left out because of negligible sand supply in all inspected years.

Figures 1 to 3 show the results of the model-based policy scenario simulations. Figure 1 (a) displays the sand tax rate under policy scenario OutTax as a function of the corresponding reduction of total sand extraction in all considered extracting (exporting) countries.[16] The resulting function is positive, convex and increasing, which reflects increasing marginal abatement costs. A tax rate of US-\$10 (US-\$20) per (metric) ton of sand achieves an output reduction of almost 60% (respectively, 70%). Figure 1 (b) displays the corresponding graphs for the sand tax under scenarios ImpTax and ExpTax. While the shape of the curves mimics that of the curve in figure 1 (a), skyrocketing tax rates of US-\$100 (US-\$700) per ton of sand induce only a 1.5 to 2% (respectively, 2.5 to 3%) output reduction. There are two explanations. First, taxation of traded sand induces a shift from exports to domestic sales in the exporting countries and, in the case of Singapore's import tax (ImpTax), a shift to other importers (among the Southeast Asian countries considered in the model). Second, especially in *MYS, PHL* and

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[16] To obtain this relationship, either the sand tax rate or the reduction amount (*SEATS*) is fixed, while the other one emerges endogenously. The total sand extraction is calculated as the sum of extracted quantities in all extracting countries.

VNM, the benchmark data for 2011 obtained from the official statistics contain substantial amounts of domestic sand sales (see table A5 of the Appendix). Trade policy, however, is not able to reduce domestic sales. The export tax achieves a slightly smaller reduction of sand extraction than that achieved by the import tax because the former generates revenues within the exporting countries that are to some extent spent on domestically extracted sand.[17]

– Figures 1, 2 and 3 about here. –

Figures 2 and 3 depict country-specific relative welfare effects (where gains are positive) as a function of the corresponding reduction of total sand extraction. The major exporters can achieve welfare gains by imposing a uniform export tax on sand in all exporting countries (ExpTax), whereas the minor exporters lose. With a total sand extraction reduction of 2.6%, the largest exporter *KHM* achieves the maximum welfare gain of 60%, and *MMR* achieves ca. 1.4% gain compared to the benchmark scenario of having no sand policy, notably, at an unrealistic tax rate of approximately US-$800 per ton. If the export tax is replaced by the Singaporean import tax (ImpTax), all exporters will become worse off than without any sand policy because the tax revenues accrue to *SGP*. The welfare effects of the import tax are, however, small (far below 1%). *SGP*, on the contrary, gains almost 3% from the import tax but loses almost 3% due to the export tax, compared to the benchmark scenario of no sand policy.

The use of the output tax in all exporting countries (OutTax) results in a positive, convex and increasing welfare effect as a function of the corresponding sand reduction for all exporters.[18] Whereas the total sand extraction can be reduced by approximately 70%, the achievable welfare gains vary from 0.06% in *MYS* and *MMR* to over 0.3% in *PHL* and *VNM*, and up to 1.4% in *KHM*. SGP's corresponding welfare effect mirrors those of the exporters: the welfare effect as a function of the sand reduction is negative, concave and decreasing; the magnitude of the welfare loss reaches 0.08%.

Figures R1 to R3 in the Appendix illustrate the corresponding simulation results for the HigDem scenario with the assumption that *SGP*'s sand demand will increase fivefold compared to the previous standard policy scenarios. According to this robustness check, the welfare effects of the export tax (ExpTax/HigDem) that are negative for the importer *SGP* but positive for the exporters, rise by almost an order of magnitude (except in *PHL*) compared to the standard scenario (ExpTax). The corresponding

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[17] The import tax does not create this effect in *SGP* because *SGP* does not possess domestic sand reserves.

[18] The extension of the solution scope would probably lead to a welfare maximum (the optimal tax) and a consecutive decline in the positive welfare effects. Because of the relatively low sand demand elasticity, the scope of feasible model solutions encompasses the rising branch before the maximum only.

maximum achievable total sand reduction more than doubles to 7.5% under ExpTax/HigDem and 8.0% under ImpTax/HigDem (figure R1 (b)). The welfare gain that SGP can achieve via the import tax (ImpTax/HigDem) remains the same as before (3% under ImpTax). Most welfare effects and the corresponding total sand reductions induced by the output tax (OutTax/HigDem), in contrast, hardly change compared to the respective values under the standard scenarios, except in *SGP* and *MMR,* where welfare effects rise by almost an order of magnitude compared to the effects under the standard scenario (OutTax).

Discussion

The most characteristic feature of the analyzed model is the detailed, theory-based representation of international trade. The model structure and the simulations draw on benchmark data from official statistical bureaus describing the current economic environment. Thus, the model is tailored to studying the effects of taxation on international trade given the current trade patterns.

If scholars or policymakers intend to study long-term developments and policies, a Hoteling type model of intertemporally optimal resource extraction with a limited, nonrenewable sand deposit can be the preferable model type. Our analysis has a short- to medium-term perspective. It assumes that sand deposits are (at least to some extent) renewable or available in sufficient quantities within the examined time horizon. A long-term analysis would be complicated by uncertainty of technical progress, which might substantially reduce the need for sand in construction or even make it obsolete.

Unofficial sand trade is not captured by the data. Therefore, we have performed a robustness check with extended sand demand and hence trade. The robustness check has demonstrated that future changes in Singapore’s sand demand can create greater than proportional changes in welfare effects for both Singapore as the sand importer, and sand exporters. These changes can likely reach an order of magnitude. On the one hand, no precise official forecasts of Singapore’s sand demand are available. On the other hand, any forecast of sand demand, supply and trade is subject to uncertainty of future economic growth and technical progress that might introduce alternative less sand-intensive production techniques and thus reduce sand demand. Therefore, the prediction of future sand demand is the primary source of uncertainty. Nonetheless, the advantages of pricing sand extraction (OutTax), implemented either as a tax or via the *SEATS*, are qualitatively robust to the sensitivity check.

The simulation results have revealed substantial differences between the effects of trade policy and output taxation. These differences hinge on the implicit possibility of shifting sand sales in the model from the export to the domestic market. If this possibility becomes more restricted and more of the extracted sand is shipped to Singapore, the effects of trade policy will be closer to those of output taxation, i.e., the trade policy will become more effective with respect to the reduction of sand extraction.

To assess the uncertainty in key model parameter values, we perform a sensitivity analysis. The results are shown in figures S1 to S3 of the Appendix. First, we lower and raise the parameter values governing the trade elasticity in all sectors by one standard deviation (based on the estimates of Caliendo and Parro, 2015). The effect on sand extraction and welfare is close to zero under OutTax and is small under ExpTax. Second, we change the elasticity of substitution between intermediate inputs in the construction (*CONS*) and nonmetallic minerals (*NMMS*) sectors from 0 to 0.25 and 0.75,[19] which varies the substitution possibilities between inputs within a moderate range. The effect on sand extraction and welfare is significant. For instance, the achievable sand reduction via the export tax doubles, and SGP's welfare loss created by the output tax decreases by 50% if 0.75 is assumed. Although these effects are dominated by the uncertainty of the future sand demand discussed above, alterations of elasticities can increase or decrease the differential between the effects of trade policy and output taxation.

Another unknown factor is the socially optimal rate of the sand tax, i.e., the correct rate of the Pigou tax that reflects the total social (especially environmental) marginal damage. Because this information is unavailable to date, this analysis has exploited a wide range of feasible tax rates. From a modeling perspective, feasibility refers to the solution space of well-defined, unique market equilibria. From a policy perspective, feasibility refers to reasonable tax rates as depicted by figure 1. Such tax rates reach nearly US-$20 per ton under the OutTax scenario. Given sand prices have been between approximately US-$4 and 9 per ton during the preceding ten years (UN Comtrade, 2016, Statista, 2018), the price of US-$20 per ton implies very substantial taxation. Tax rates reaching hundreds of dollars, as examined in the trade policy scenarios ExpTax and ImpTax, appear to be prohibitively high and politically unrealistic. Against this backdrop, the range of tax rates examined in this analysis seems to be sufficient with regard to practical policy implications.

Conclusion

The presented simulation results are in favor of a uniform output tax (OutTax) imposed on the total sand extraction in all sand extracting (exporting) Southeast Asian countries. The output tax can achieve a wide range of reductions of sand extraction at moderate marginal costs represented by moderate tax rates.

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[19] These two sectors absorb most of the sand supply. The value of zero implies that there are no substitution possibilities between different inputs.

Once more accurate and complete information about the total social (including environmental) marginal damage of sand extraction has become available, an appropriate rate of the corresponding *Pigou* tax can be derived and implemented. While all sand exporters gain from the output tax policy due to higher gross sand prices (including the tax) and resulting tax revenues, Singapore's welfare losses are minor. The output tax can equivalently be implemented as a *Sand Extraction Allowances Trading Scheme (SEATS).* Notably, the output tax goes beyond Singapore's responsibility for the externalities of its sand consumption, because such taxation significantly affects *domestic* sand sales of the Southeast Asian sand extractors. The policy implementation, however, poses challenges. In particular, it requires coordinated action by the exporters to implement the uniform tax rate and capture the entire sand extraction market.

If only a part of the sand market is taxed – as in the export tax (ExpTax) or import tax (ImpTax) scenarios – the untaxed part of the market will absorb most of the excess sand supply. This effect renders both trade policies rather ineffective for reducing sand extraction. Although not explicitly visible in the model, the untaxed market may include illegal sales and exports that undermine any taxation or regulation of legal sand extraction and trade. Thus, full coverage and strict monitoring of sand taxation in all exporting countries are inevitable.

The export tax scenario (ExpTax), on the contrary, has the advantage of benefiting the poorest exporters, Cambodia and Myanmar. The estimated magnitude of this gain based on data for the benchmark year 2011, however, is only significant for Cambodia and small for Myanmar, whereas the other exporters are slightly worse off than without a sand policy. The robustness check (HigDem) indicates that Singapore's expected increasing future sand demand can enlarge the welfare effects of the export tax by an order of magnitude.

The primary advantage of the import tax (ImpTax) policy is the opportunity for Singapore to implement it unilaterally following its green economic attitude without the requirement of international coordination. In this sense, the import tax can act as a temporary compromise as long as a coordinated policy on the export side covering the entire sand extraction cannot be achieved. Nonetheless, policymakers should engage in international negotiations to capture the social and environmental benefits of the output tax (OutTax). The potential welfare gains should create the right economic incentive for the Southeast Asian exporters, while the "green frontrunner" role should create an incentive for Singapore.

The socially optimal policy implementation requires the search for more precise information on the damage of sand extraction. Once natural science scholars have provided this information, economics scholars can derive the corresponding costs and contrast them with related benefits. Political scientists may explore the approaches to the coordinated tax policy implementation. In this way, Singapore can serve as a prominent example that demonstrates how the sand extraction problem can be successfully solved or at least mitigated. The resulting insights will be of global relevance because of the immense importance of sand as an essential input to construction all over the world. Although this study will not resolve the global problem of harmful sand extraction and limited sand reserves, it has demonstrated that smart policies can, at least to some extent, reconcile Singapore's green economy with sand imports from Southeast Asia if such policies are implemented and controlled rigorously. In this way, it is hoped that this study has pointed to a promising avenue for further research.

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Figures & Appendix

Can Smart Policies Reconcile Singapore's Green Economy with Sand Imports from Southeast Asia?

Michael Hübler[*], Frank Pothen [†]

November 17, 2018

Abstract

In part I, this Appendix provides the main figures with simulation results to be included in the main article as well as supplementary figures showing descriptive statistics, a robustness check and sensitivity analysis results to be uploaded as supplementary online materials. In part II, it provides the supplementary online appendix. The online appendix first describes, in a nontechnical way, the model setup in terms of represented regions and sectors as well as functional forms. Based on that information, the appendix describes the data sources of the numerical model calibration. It then explains the representation and disaggregation of the sand sector and the definition of the related policies. The final section provides the mathematical formulation of the model.

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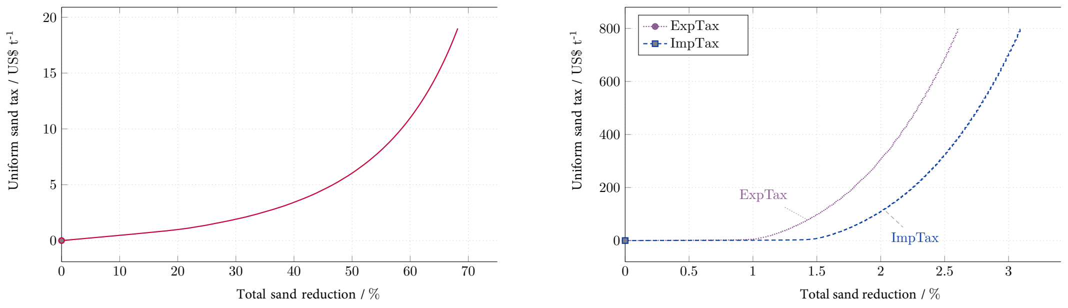
I Figures

Main simulation results

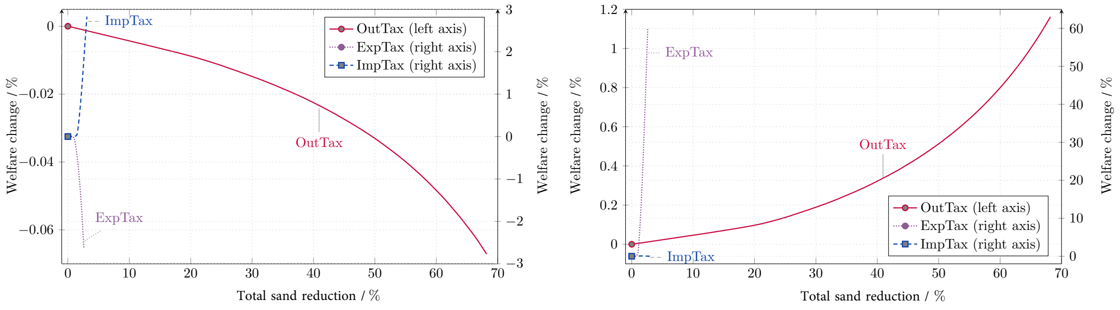
The following figures show the main simulation results to be included in the main article. Figure 1 depicts the sand tax rate as a function of the reduction of total sand extraction in all sand extracting (exporting) Southeast Asian countries. These graphs can be interpreted as marginal abatement cost curves. Figures 2 and 3 show countries' relative welfare changes vs. the reduction of total sand extraction.

Figure 1
Marginal abatement cost curves



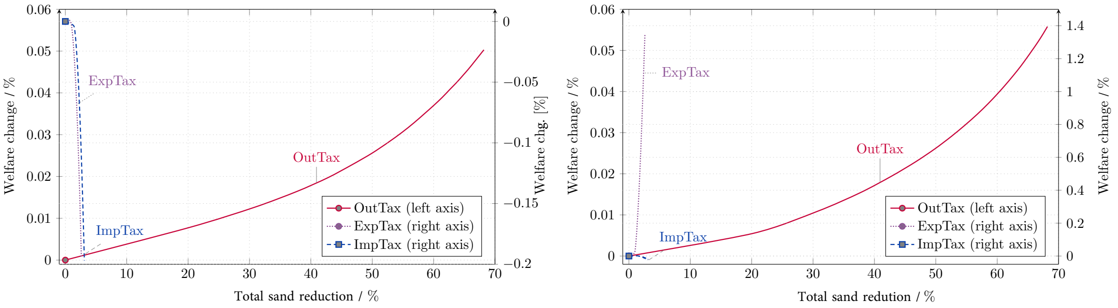
(a) Output tax (OutTax) (b) Export (ExpTax) & import tax (ImpTax)

Figure 2
Regional welfare effects



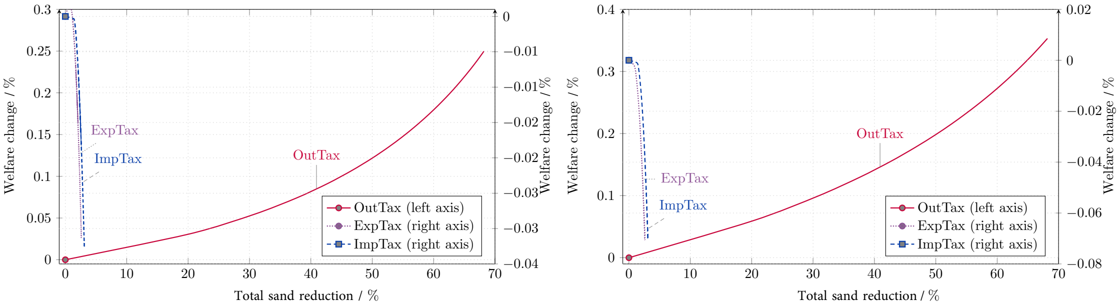
(a) Singapore (*SGP*) (b) Cambodia (*KHM*)

Figure 3
Regional welfare effects



(a) Malaysia (MYS)

(b) Myanmar (MMR)



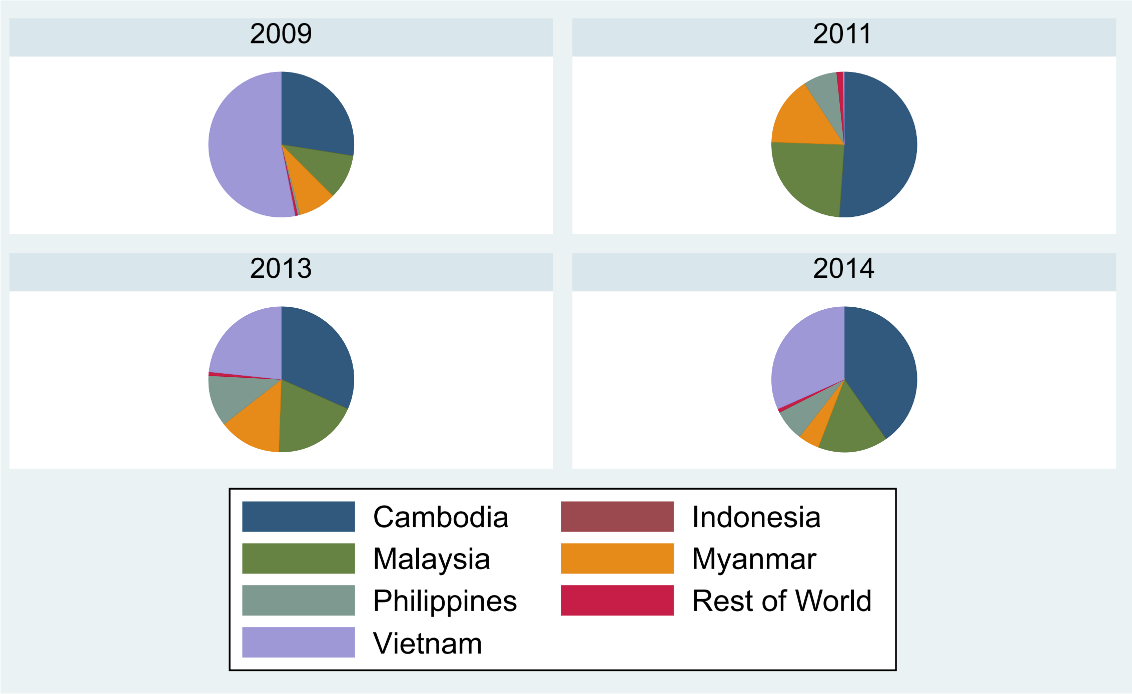
(c) Philippines (PHL)

(d) Vietnam (VNM)

Supplementary descriptive statistics

All figures presented in the following sections are supplementary. Figure D1 displays the distribution of Singapore's (SGP's) sand and gravel imports (data classifications H1–H3) by source countries based on import values for recent years as published in the United Nations Comtrade database in 2015/16 (UN Comtrade, 2016). In accordance with these data, the subsequent policy analysis will concentrate on the largest sand suppliers: Cambodia (KHM), Malaysia (MYS), Myanmar (MMR), the Philippines (PHL) and Vietnam (VNM). Note that in the model's benchmark year 2011, Vietnam's sand exports to Singapore were small. Because Indonesia's sand exports were minor in all years, Indonesia is left out of the analysis.

Figure D1
Distribution of Singapore's sand imports

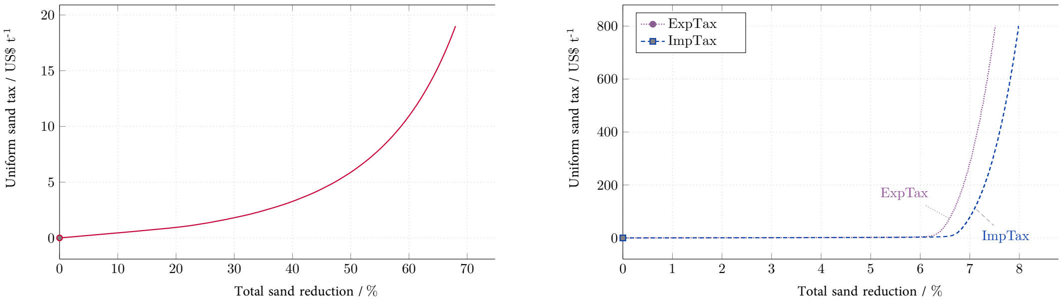


By source countries (UN Comtrade, 2016)

Supplementary robustness check

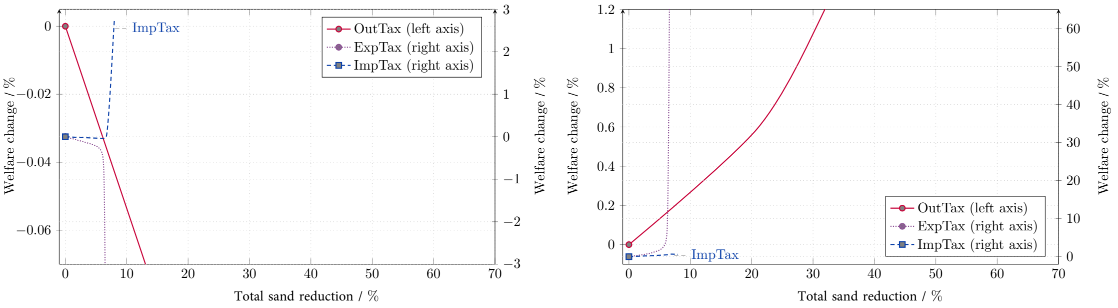
As a robustness check, the following figures show alternative simulation results under the assumption that Singapore's (*SGP*'s) sand demand increases fivefold (HigDem). Figure R1 depicts the sand tax rate as a function of the reduction of total sand extraction in all sand-extracting (exporting) Southeast Asian countries. The graphs can be interpreted as marginal abatement cost curves. Figures R2 and R3 show countries' relative welfare changes vs. the reduction of total sand extraction.

Figure R1
Marginal abatement cost curves with extended sand demand



(a) Output tax (OutTax/HigDem) (b) Exp. (ExpTax/HigDem) & imp. tax (ImpTax)

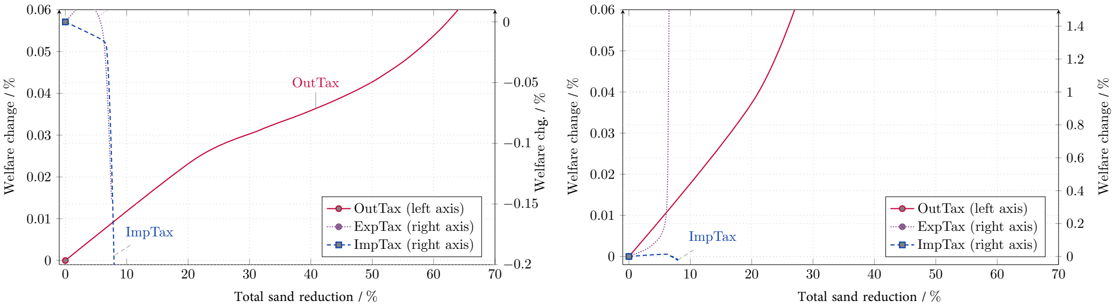
Figure R2
Regional welfare effects with extended sand demand



(a) Singapore (SGP/HigDem)

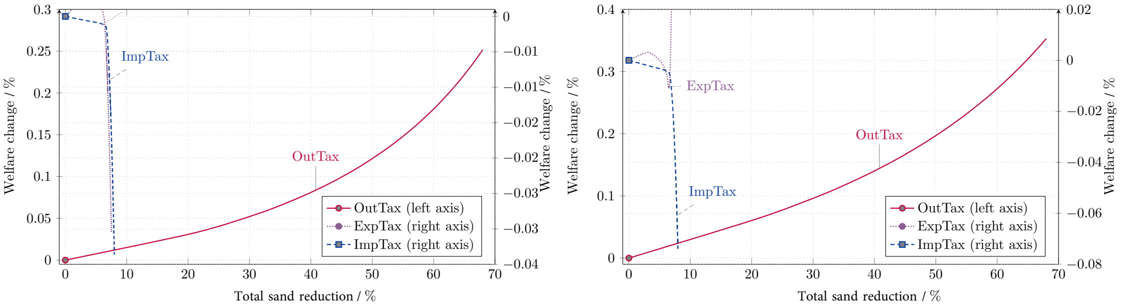
(b) Cambodia (KHM/HigDem)

Figure R3
Regional welfare effects with extended sand demand



(a) Malaysia (MYS/HigDem)

(b) Myanmar (MMR/HigDem)



(c) Philippines (PHL/HigDem)

(d) Vietnam (VNM/HigDem)

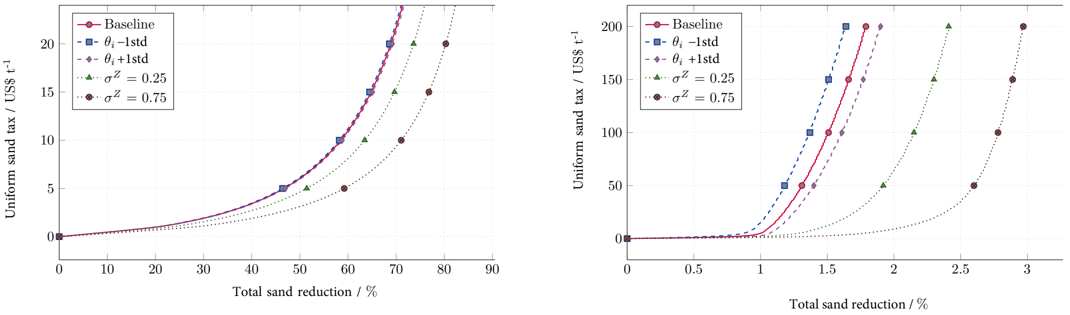
Supplementary sensitivity analysis

The following figures show the simulation results of the supplementary sensitivity analysis. First, we vary the trade elasticity parameter values θ_i of all sectors i by ± one standard deviation. The means (as reported in table A4) and standard deviations are taken from Caliendo and Parro (2015). The remaining standard deviations corresponding to the means taken from Eaton and Kortum (2002) are set to one.

Second, the construction ($CONS$) and non-metallic minerals ($NMMS$) sectors absorb most of the total sand supply. Hence, we change the standard value of $\sigma^Z = 0$, i.e., the elasticity of substitution between intermediate inputs including sand (as illustrated in figure A2 and reported in table A3), in these two sectors to 0.25 and 0.75, respectively. The discussion section of the main article summarizes and interprets the results.

Figure S1

Margin. abatem. cost curves with variation in trade and input elasticities

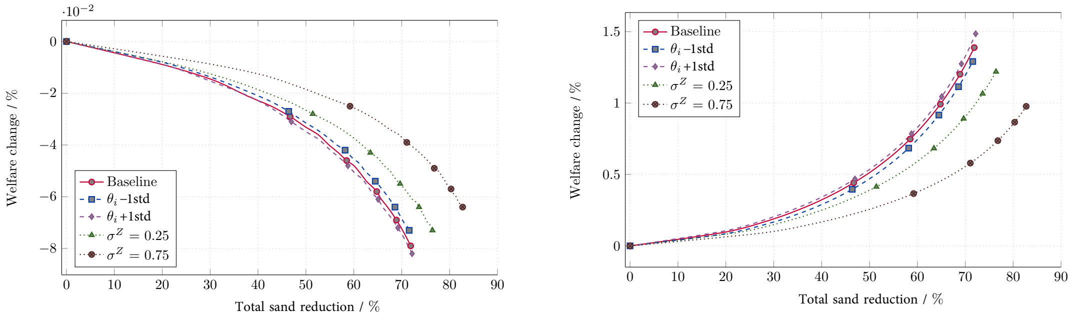


(a) Output tax (OutTax)

(b) Export tax (ExpTax)

Figure S2

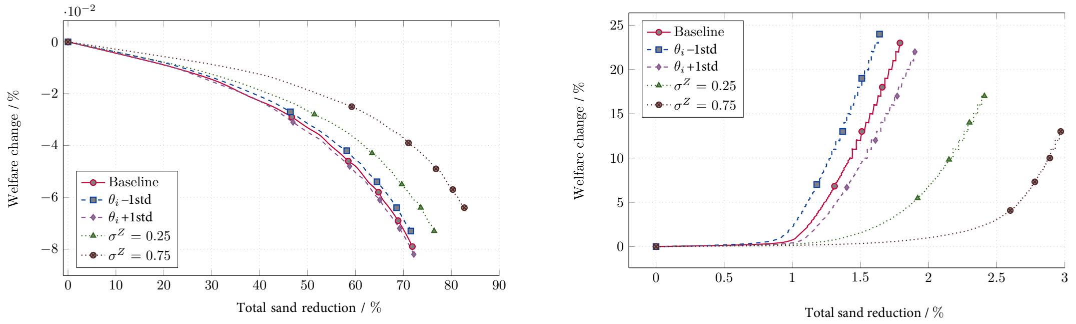
Regional welfare effects with variation in trade and input elasticities



(a) Output tax (OutTax), Singapore (SGP)

(b) Output tax (OutTax), Cambodia (KHM)

Figure S3
Regional welfare effects with variation in trade and input elasticities



(a) Export tax (OutTax), Singapore (*SGP*)   (b) Export tax (ExpTax), Cambodia (*KHM*)

II Appendix

1 Basic model structure

1.1 Regions

Table A1 lists 16 model regions r (alternatively, s). The column *SAND* indicates whether there is a sand extracting sector in r.

Table A1
Regions in the model

r	Region	$SAND$	r	Region	$SAND$
KHM	Cambodia	Yes	KOR	Korea, Republic of	No
MYS	Malaysia	Yes	TWN	Taiwan	No
MMR	Myanmar	Yes	IDN	Indonesia	No
PHL	Philippines	Yes	USA	United States	No
VNM	Vietnam	Yes	EUR	Europe (EFTA)	No
SGP	Singapore	No	JPN	Japan	No
THA	Thailand	No	ROA	Rest of Asia	No
CHN	China	No	ROW	Rest of the World	No

1.2 Sectors

Table A2 presents 16 model sectors (goods) i (alternatively, j). The investment good sector *INVS* provides a nontradable good and is hence excluded from the analysis of international trade. It is not used as an intermediate good input either. All other goods can either be used for final consumption or as intermediate inputs in production. Section 5.5 will additionally introduce international (global) transport services, which are required for shipping goods but are not treated as a normal production sector.

Table A2
Sectors in the model

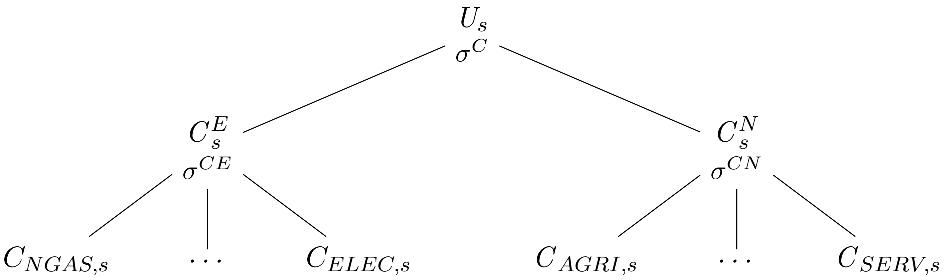
i	Sector
$AGRI$	Agriculture
$COAL$	Coal
$CRUD$	Crude oil
$NGAS$	Natural gas
$PETR$	Refined petroleum
$FOOD$	Food production
$SAND$	Sand and gravel
$OTMN$	Other mining excl. sand
$MANU$	Manufacturing
$NMMS$	Non-metallic minerals
$EINS$	Energy-intensive sectors
$ELEC$	Electricity
$TRNS$	Transport
$CONS$	Construction
$SERV$	Services
$(INVS$	Investment)

2 Nested CES functions

2.1 Consumption

In each model region s, a representative consumer maximizes her utility U_s by choosing the optimal consumption bundle of all composite goods. She has nested constant elasticity of substitution (CES) preferences over sectoral composites. The preference structure is depicted by figure A1. The nested preferences allow for a differentiated degree of substitutability between individual goods in different nests. σ denotes the elasticity of substitution between goods in each nest.

Figure A1
Nesting structure of the consumption (utility) function

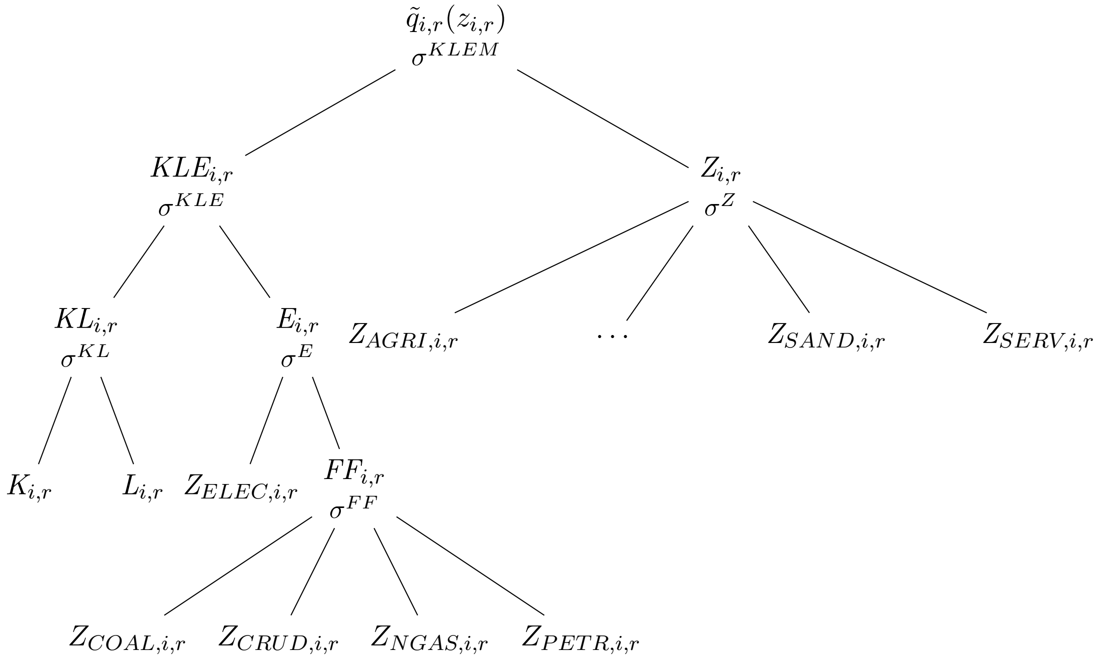


At the top level, the function combines a bundle of energy goods C_s^E with a non-energy bundle C_s^N. The elasticity of substitution between them is denoted by σ^C. The consumption of energy goods coal ($COAL$), crude oil ($CRUD$), gas ($NGAS$), refined petroleum ($PETR$) and electricity ($ELEC$) is aggregated in the energy bundle C^E_s. The elasticity of substitution between energy goods is σ^{CE}. C^N_s is the corresponding bundle of non-energy goods combined with the elasticity σ^{CN}.

2.2 Production

In each sector i of each region r, representative producers provide a continuum of differentiated varieties of the sector's good. They use the primary factors of labor $L_{i,r}$ and capital $K_{i,r}$ as well as intermediate inputs from all sectors as inputs. The producers minimize their input costs subject to the production function (technology) depicted in figure A2 by choosing the cost-minimizing input bundle $\tilde{q}_{i,r}(z_{i,r})$. Whereas most Eaton and Kortum (2002) type models assume that factors and intermediate inputs are combined in a Cobb-Douglas fashion, the underlying model follows Pothen and Hübler (2018) by implementing a nested CES production structure.

Figure A2
Nesting structure of the production function



Inputs of labor $L_{i,r}$ and capital $K_{i,r}$ are combined in the nest $KL_{i,r}$ assuming an elasticity of substitution $\sigma^{KL} = 1$ (Cobb-Douglas) between them. The fossil fuels nest $FF_{i,r}$ combines inputs of coal ($Z_{COAL,i,r}$), crude oil ($Z_{CRUD,i,r}$), natural gas ($Z_{NGAS,i,r}$) and refined petroleum ($Z_{PETR,i,r}$). The corresponding elasticity of substitution is denoted by σ^{FF}. The energy nest $E_{i,r}$ combines fossil fuel inputs with electricity inputs with the elasticity of substitution σ^E. This assumption reflects the idea that electricity serves a different purpose in production processes than that of fossil fuels. The inputs of energy and value added are combined in the $KLE_{i,r}$ nest with the corresponding elasticity of substitution σ^{KLE}. This structure is consistent with van der Werf (2008) who has shown that substitution between energy and value added matches the empirical data well. The aggregate $KLE_{i,r}$ is combined with non-energy intermediate inputs with the elasticity of substitution σ^{KLEM} to obtain the cost-minimal input bundle $\tilde{q}_{i,r}(z_{i,r})$. Individual non-energy inputs are aggregated in the nest $Z_{i,r}$ with the elasticity of substitution $\sigma^Z = 0$ (Leontief). Intermediate inputs of $SAND$ are also included in the non-energy input nest $Z_{i,r}$. Accordingly, the demand for $SAND$ does not react elastically to changes in prices because sand is (currently) an indispensable input in construction.

3 Model calibration

3.1 Input-output data

The Global Trade Analysis Project (GTAP) dataset, version 9 (Aguiar et al., 2016) is the main data source providing input-output data for the benchmark year 2011. The data cover consumption, production and international trade as well as policy parameters such as subsidies and taxes. These data are used to calibrate the input value shares[1] and corresponding outputs of the CES functions described in section 2.

Data on sand and gravel trade are taken from UN Comtrade (2016). We use two six-digit harmonized system (HS) items to quantify the flows of sand: HS 250590 (sands; natural, other than silica and quartz sands, whether or not colored, other than metal-bearing sands of chapter 26) and HS 2517 (pebbles, gravel, crushed stone for concrete aggregates for road or railway ballast, shingle or flint; macadam of slag, dross, etc., tarred granules, chippings, powder of stones of heading No. 2515 and 2516).[2] The physical extraction of sand and gravel is taken from the materialflows.net database (Lutter et al., 2015).

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[1] A larger input value share implies larger economic effects of changing this input.

[2] For MMR, we use data for 2010 because there are no physical export data available for 2011. For VNM and MYS, we use the average of the other three regions as physical exports are unavailable (VNM) or the implied prices are implausibly high (MYS).

3.2 CES elasticities

The CES functions characterized in section 2 require the choice of elasticities of substitution, which are not covered by input-output datasets. Because the design of our model has been inspired by the established MIT EPPA (Emissions Prediction and Policy Analysis) model (Paltsev et al., 2005), we draw on the elasticities of substitution used there.

Table A3
CES elasticities of substitution

	Elasticity of substitution between	Value
Consumption:		
σ^{CE}	Energy goods	0.40
σ^{CN}	Non-energy goods	0.25
σ^{C}	Energy and non-energy aggregates	0.25
Production:		
σ^{KLEM}	KLE and intermediates	1.50
σ^{KLE}	Value added and energy	0.40
σ^{Z}	Non-energy intermediates	0.00
σ^{KL}	Capital and labor	1.00
σ^{E}	Electricity and fossil fuels	0.50
σ^{FF}	Fossil fuels	1.00
σ^{Q}	Varieties	2.00

σ = elasticity of substitution; values are taken from Paltsev et al. (2005).

Table A3 presents the used values of the elasticity of substitution σ. They are assumed to be equal across all sectors and regions. A larger elasticity implies better substitutability between the attached inputs and hence more flexibility in terms of adjustments to policy changes. As a consequence, negative welfare effects of taxation will likely become smaller.

3.3 Trade elasticities

Table A4 displays the values of the sector-specific shape parameter of the Fréchet distribution θ_i required for the Eaton and Kortum trade model. Whenever possible, the values are based on Caliendo and Parro (2015). In sectors, for which no estimate is available, we use the value of 8.28 according to Eaton and Kortum (2002). A larger value of θ_i reflects a narrower distribution and hence less variation in productivities (Pothen and Hübler, 2018) resulting in less flexibility in terms of adjustments to policy changes. As a consequence, the possible gains from trade via Ricardian specialization in varieties (Eaton and Kortum, 2002) will decrease, and policy impacts on trade will likely become stronger.

Table A4
Sectoral trade elasticities

i	Sector	θ_i	Source
$AGRI$	Agriculture	9.11	CP, agriculture
$COAL$	Coal	13.53	CP, mining
$CRUD$	Crude oil	13.53	CP, mining
$NGAS$	Natural gas	13.53	CP, mining
$PETR$	Refined petroleum	64.85	CP, petroleum
$FOOD$	Food production	2.62	CP, food
$SAND$	Sand and gravel	13.53	CP, mining
$OTMN$	Other mining excl. sand	13.53	CP, mining
$NMMS$	Non-metallic minerals	2.41	CP, minerals
$EINS$	Energy-intensive sectors	3.13	CP, chemicals
$ELEC$	Electricity	12.91	CP, electrical
$MANU$	Manufacturing	8.28	EK
$TRNS$	Transport	8.28	EK
$CONS$	Construction	8.28	EK
$SERV$	Services	8.28	EK

CP = Caliendo and Parro (2015, p. 18, 99% sample) with the corresponding sector's name in CP; EK = Eaton and Kortum (2002); i = sector; θ_i = EK parameter governing the trade elasticity.

4 The sand sector

4.1 Functional form

The design of the sand sector ($SAND$) follows the CES production function (technology) utilized by the other sectors and illustrated in figure A2.

4.2 Disaggregation

The GTAP 9 database (Aguiar et al., 2016) contains an other mining (OMN) sector, which encompasses the extraction of metals and non-metallic minerals. This subsection describes how the OMN sector is decomposed into a sand and gravel sector ($SAND$) and the remaining other mining sector ($OTMN$). We perform this decomposition for six countries in South-East Asia, i.e., Singapore (SGP) and the five countries that supply the vast majority of Singapore's sand and gravel imports: Cambodia (KHM), Myanmar (MMR), Malaysia (MYS), the Philippines (PHL) and Vietnam (VNM).

Data from two sources are used to decompose the OMN sector. First, imports and exports in both physical and monetary terms are obtained from the UN Comtrade (2016) database. Second, the physical extraction of sand and gravel is obtained from the materialflows.net database (Lutter et al., 2015).

We use the UN Comtrade data for monetary flows of $SAND$ between countries. The domestic use of $SAND$ (i.e., the amount of $SAND$ used in region r that has been produced by region r itself) is not recorded in the UN Comtrade data. Hence, we estimate the amount by subtracting all physical exports of $SAND$ from r's extraction and then multiplying this quantity by the price of $SAND$. This price is approximated by comparing the monetary and physical $SAND$ exports to Singapore. Adding up the purchases of domestically produced and imported $SAND$ yields the total purchase of $SAND$ in each region. As a result, we obtain the following monetary input table for $SAND$, where $SAND$ use is reported in each column, while $SAND$ supply is reported in each row.

Table A5
Sand trade between model regions (in billions of 2011-US$)

	SGP	KHM	MMR	MYS	PHL	VNM
SGP	0.000	0.000	0.000	0.000	0.000	0.000
KHM	0.091	0.008	0.000	0.000	0.000	0.000
MMR	0.027	0.000	0.000	0.000	0.000	0.000
MYS	0.037	0.000	0.000	0.536	0.000	0.000
PHL	0.014	0.000	0.000	0.002	0.367	0.000
VNM	0.001	0.000	0.000	0.001	0.001	1.430

Using these data on $SAND$ flows, we can decompose the OMN sector in the six countries. First, we split the demand for OMN in each region into demand for $SAND$ and $OTMN$ by making the following assumptions:

1. Demand for OMN by the construction sector ($CONS$) is allocated to $SAND$.
2. Demand for OMN by the non-metallic mineral sector ($NMMS$) is assumed to be 50% $SAND$ and 50% $OTMN$.
3. Final demand and investment are assumed to use only $SAND$ but not $OTMN$.
4. Remaining $SAND$ demand is allocated to the remaining sectors proportionally to the sectors' share in total production.

Next, we decompose the trade flows of OMN. In some cases, particularly those of $SAND$ exports from KHM, PHL, and MMR to Singapore, the flows of OMN between countries recorded in the Comtrade data exceed the $SAND$ flows in GTAP. Therefore, we increase the GTAP trade flows to match those in Comtrade. To ensure that the accounting identities remain satisfied, we increase the outputs of the OMN sectors in the supplying countries as well as the corresponding labor inputs. Correspondingly, we need to increase the supply of international transport margins because the additional trade requires transport services. We assume that the additional services are provided by the USA.[3] Except the 17% tax on sand in Vietnam, there are no export tariffs on $SAND$ in 2011 (see OECD, 2018). We obtain import tariffs as well as taxes on OMN for $SAND$ and $OTMN$. Note that Singapore does not levy import tariffs on OMN and thus $SAND$.

Finally, we disaggregate the trade flows (including domestic supply) of OMN into flows of $SAND$ and $OTMN$, ensuring that there is no negative domestic supply of $OTMN$. If necessary, we reduce the demand for $OTMN$ by lowering investments $INVS$. Thereafter, we are able to compute the gross output of $SAND$ and $OTMN$. The inputs into production of OMN are split into inputs in $SAND$ and $OTMN$ according to their shares in the gross output of OMN. Adjusting the income and current account deficits in all regions concludes the disaggregation of the OMN sector.

4.3 Future demand

In the alternative robustness check scenario HigDem, we multiply the sand demand in the year 2011 by a factor of five. This choice is due to two considerations. First, in the UN Comtrade (2016) data, sand trade varied between different past years by a factor of 3.5 (cf. figure D1). Second, based on several estimates (Foreign Policy, 2010; The Asia Miner, 2014; FAZ, 2016), Singapore's planned future sand reclamation projects will increase its sand demand by a factor of between 1.7 and 6.8.

4.4 Historical policies

Historically, the $SAND$ sector has been subject to various policies, particularly export bans in Vietnam and Malaysia. To eliminate these export bans, we recalibrate the model such that all trade barriers to $SAND$ trade are zero. Although we can set the export tariffs to zero, the effect of the export bans must be estimated. To this end, we apply ordinary least squares (OLS) to the econometric model in (1) to quantify the impact of

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[3] We increase the labor input into the USA's transport sector such that its output and input values equal each other. The USA has been chosen because it is the world's largest economy. As a result of the data adjustment, the output of the USA's transport sector increases by less than one per mill, making the assumption innocuous.

export bans.

$$\log\left(\frac{\pi_{SAND,r,s}}{\pi_{SAND,s,s}}\right) = E_r - E_s - \theta_i\left(\log\tau^t_{SAND,r,s} + \log\tilde{\delta}_{SAND,r,s}\right) + \varepsilon_{r,s} \tag{1}$$

$\pi_{SAND,r,s}$ denotes the trade share, the fraction of $SAND$ that region r exports to region s. E_r and E_s are exporter and importer fixed effects that represent a combination of production costs and productivity in the $SAND$ sector of regions r and s, respectively. $\tau^t_{SAND,r,s}$ captures the observable trade costs that include tariffs and transport costs. The iceberg trade costs, which depend on whether there is a ban in force on exports from region r to s, are denoted by $\tilde{\delta}_{SAND,r,s}$. They are approximated by equation (2). $\varepsilon_{r,s}$ is an idiosyncratic error term.

$$\log\tilde{\delta}_{SAND,r,s} = \mu\log dist_{r,s} + \beta ban_{r,s} \tag{2}$$

$dist_{r,s}$ represents the geographical distance between the regions r and s, and μ is the elasticity of iceberg trade costs with respect to this distance. The dummy variable $ban_{r,s}$ equals one if there is a ban in force on exports from r to s. The coefficient β quantifies the impact of this ban on iceberg trade costs. We only observe very few trade flows for $SAND$; therefore, we do not include other dummies in equation (2).

4.5 Examined policies

In the scenario simulations, a uniform sand-specific tax on top of the market price of sand internalizes the social (environmental) damages of sand extraction. This sand tax is implemented differently in several counterfactual policy scenarios; it is denoted by $\tau^{S'}$ and measured in US$ per ton. It can be implemented as an exogenous tax or emerge as an endogenous market outcome of a Sand Extraction Certificate Trading System (SEATS) with a given limit of sand extraction.

We assume that the marginal social damages created by sand extraction are proportional to the amount of sand (and gravel) extracted in r, labeled S_r and measured in tons. Let $X_{SAND,r}$ denote the monetary value in the baseline scenario of sand sales measured in US$. Then, a sand intensity $\frac{S_r}{X_{SAND,r}}$ can be defined for the baseline to characterize the amount of sand extracted per monetary unit of sand sold, measured in tons per US$. This quantity differs across regions r but is assumed to stay constant across the scenarios for each r. Thus, if, for example, the output $Q_{SAND,r}$ of the sand sector in r measured in real currency units increases by one percent in a counterfactual scenario, S_r will rise by one percent as well. This assumption is required for the distinct policy implementations.

In the policy analysis, we investigate the effects of three types of sand taxes: an export tax (export tariff in scenario ExpTax) imposed on the sand sector of all sand-exporting regions, an import tax (import tariff in scenario ImpTax) levied in Singapore and an output (sales) tax (in scenario OutTax) on all deliveries (total extraction) of sand.

Depending on the scenario, we convert the sand tax into an ad valorem export, import or output (sales) tax (or, respectively, tariff) to ease the implementation in the model and to mimic the implementation of real-world policies. In this conversion, we consider the existence of regional differences in sand intensities.

To illustrate this conversion, we derive Singapore's import tax. Similar to the implementation procedure of border carbon adjustments, the sand tax $\tau^{S'}$ per unit of sand is multiplied by the exporter-specific sand intensity and divided by the counterfactual sand price measured relative to the baseline to eliminate monetary effects. This procedure yields a dimensionless exporter-specific ad valorem import tariff $\tau^{m'}_{SAND,r,s}$ required for the counterfactual policy scenario, which reflects the physical sand content of sand trade from r to s measured in pecuniary terms.

The corresponding transformations result in the ad valorem export tax rate ($\tau^{e'}_{SAND,r,s}$) and the ad valorem output (sales) tax rate ($\tau^{o'}_{SAND,r}$). Whereas the revenues from the import tax are distributed to Singapore's (SGP's) representative consumer as a lump sum, the revenues from the other taxes are redistributed to the consumer of the corresponding sand-extracting region r. While the output tax affects the total sand sales (extraction), the export tax affects the exported fraction only.

5 Mathematical formulation

5.1 Approach

The following sections express the model in mathematical terms. The underlying general equilibrium model is formulated as an MCP (Mixed Complementarity Problem), programmed in GAMS (General Algebraic Modeling System; Bussieck and Meeraus, 2004) and solved by using the PATH algorithm (Dirkse and Ferris, 1995). The trade model setup follows the implementation of the theory of Eaton and Kortum (2002) by Caliendo and Parro (2015) and Pothen and Hübler (2018). This section details the model consisting of equations derived from zero-profit conditions or the theory of Eaton and Kortum (2002) (subsections 5.2 to 5.5), market clearing conditions (subsection 5.6), the income balance condition (subsection 5.7) and policy-related constraints (subsection 5.8).

The model equations are written in terms of relative changes. They characterize a counterfactual (scenario) value relative to the baseline value normalized to unity, e.g., 1.1 in the counterfactual scenario compared to 1.0 in the baseline implies a 10% increase in the variable under consideration. In the literature based on Eaton and Kortum (2002), this formulation is known as "exact hat algebra" (Dekle et al., 2008). A comparable approach in the literature based on computable general equilibrium (CGE) models is the "calibrated share form" of CES functions (Böhringer et al., 2003). Regarding the formulation in terms of changes, the model differs from that of Pothen and Hübler (2018). The formulation in terms of changes has the advantage that no structural estimation is required for model calibration.

We employ the following notation. For a model variable or parameter "x", x denotes the baseline value that is normally given by the benchmark data of the model calibration. x' denotes the corresponding value in the counterfactual simulation, and $\hat{x} = \frac{x'}{x}$ is the change between the counterfactual and the baseline, which will be applied in the following analysis. In particular, we quantify the economic effects of changing the sand tax from a baseline value of $\tau^S = 0$ to a counterfactual value of $\tau^{S'} > 0$.

5.2 Consumption

5.2.1 Cost functions

Referring to figure A1, this subsection defines the cost functions of the demand side. Equation (3) describes the change in the true-cost-of-living index between the counterfactual scenario and the baseline, denoted by $\hat{c}_s^C$. It is derived from the CES utility function with the elasticity of substitution σ^C. The variable $\hat{c}_s^{CE}$ denotes the change in the cost index of the energy aggregate, while $\hat{c}_s^{CN}$ denotes the change in the costs of the non-energy aggregate. β_s^C is the value share of the energy aggregate in the baseline.

$$\hat{c}_s^C = \left(\beta_s^C (\hat{c}_s^{CE})^{1-\sigma^C} + (1-\beta_s^C)(\hat{c}_s^{CN})^{1-\sigma^C}\right)^{\frac{1}{1-\sigma^C}} \tag{3}$$

The change $\hat{c}_s^{CE}$ in the cost index of the energy aggregate in consumption is computed similarly. It depends on the change in the price of good i ($\hat{P}_{i,s}$), the value share of this good in the energy aggregate ($\beta_{i,s}^{CE}$) and the elasticity of substitution between these goods (σ^{CE}). Any consumption tax ($\tau_{i,s}^c$) does not appear in equation (4) because the tax rate does not change between the baseline and the counterfactual scenario. We use the simplified notation $[CE]$ to symbolize the subset of energy sectors $[CE] = \{COAL, NGAS, PETR, CRUD, ELEC\}$ in the summation.

$$\hat{c}_s^{CE} = \left(\sum_{i|i \in [CE]} \beta_{i,s}^{CE} (\hat{P}_{i,s})^{1-\sigma^{CE}} \right)^{\frac{1}{1-\sigma^{CE}}} \tag{4}$$

The change in the cost index of the non-energy aggregate in consumption ($\hat{c}_s^{CN}$) is computed analogously.

$$\hat{c}_s^{CN} = \left(\sum_{i|i \in [CN]} \beta_{i,s}^{CN} (\hat{P}_{i,s})^{1-\sigma^{CN}} \right)^{\frac{1}{1-\sigma^{CN}}} \tag{5}$$

5.2.2 Demand functions

This subsection explains the demand functions. They describe the change in the representative consumer's demand for good i. To simplify the exposition, we split the complex demand functions derived from the CES utility function into per-unit demand functions for each nest. The function $\hat{d}_s^{C,CE}$, for instance, describes the change in demand for the non-energy aggregate per consumption unit:

$$\hat{d}_s^{C,CE} = \left(\frac{\hat{c}_s^{C}}{\hat{c}_s^{CE}} \right)^{\sigma^C} \tag{6}$$

The change in demand for the non-energy aggregate $\hat{d}_s^{C,CN}$ can be written analogously:

$$\hat{d}_s^{C,CN} = \left(\frac{\hat{c}_s^{C}}{\hat{c}_s^{CN}} \right)^{\sigma^C} \tag{7}$$

The expression $\hat{d}_{i,s}^{CE,i}$ represents the change in the demand for good $i \in [CE]$ per consumption unit of the energy aggregate. Again, any consumption tax $\tau_{i,s}^{c}$ does not appear in the demand function because it does not change between the baseline and the counterfactual scenario.

$$\hat{d}_{i,s}^{CE,i} = \left(\frac{\hat{c}_s^{CE}}{\hat{P}_{i,s}} \right)^{\sigma^{CE}} \quad \forall i \in [CE] \tag{8}$$

The demand for the non-energy good $i \in [CN]$ per consumption unit of the non-energy aggregate is expressed as

$$\hat{d}_{i,s}^{CN,i} = \left(\frac{\hat{c}_s^{CN}}{\hat{P}_{i,s}} \right)^{\sigma^{CN}} \quad \forall i \in [CN] \tag{9}$$

The combination of equations (6) to (9) yields the following expression for the change in consumption of good i distinguishing between energy goods and non-energy goods:

$$\hat{C}_{i,s} = \begin{cases} \frac{\hat{Y}_s}{\hat{c}_s^C} \cdot \hat{d}_s^{C,CE} \cdot \hat{d}_{i,s}^{CE,i} & \text{if } i \in [CE] \\ \frac{\hat{Y}_s}{\hat{c}_s^C} \cdot \hat{d}_s^{C,CN} \cdot \hat{d}_{i,s}^{CN,i} & \text{if } i \in [CN] \end{cases} \tag{10}$$

5.3 Production

5.3.1 Cost functions

Referring to figure A2, this subsection defines the cost functions of the production side. To this end, the per-unit cost function ($c_{i,r}$) is split into per-unit cost functions for each nest of the production technology depicted by figure A2. The variable $\hat{c}_{i,s}^{KL}$, for instance, represents the change in the Cobb-Douglas cost index of value added in the production of good i in region r. The parameter $\beta_{i,r}^{KL}$ represents the value share of capital in the $KL_{i,r}$ nest.

$$\hat{c}_{i,r}^{KL} = (\hat{P}_r^K)^{\beta_{i,r}^{KL}} \cdot (\hat{P}_r^L)^{1-\beta_{i,r}^{KL}} \tag{11}$$

Equation (12) describes the change in the cost index of the fossil fuel nest $FF_{i,r}$ of i in r, $\hat{c}_{i,r}^{FF}$. $\beta_{j,i,r}^{FF}$ denotes the value share of fossil fuel j in the FF nest. Let $[FF]$ symbolize the subset of all fossil fuel sectors $[FF] = \{COAL, NGAS, PETR, CRUD\}$ so that

$$\hat{c}_{i,r}^{FF} = \prod_{j \in [FF]} (\hat{P}_{j,r})^{\beta_{j,i,r}^{FF}} \tag{12}$$

$\hat{c}_{i,r}^{E}$ characterizes the change in the cost index of the energy nest $E_{i,r}$. The value share of fossil fuels is denoted $\beta_{i,r}^{E}$. σ^E symbolizes the nonunitary elasticity of substitution, and $\hat{P}_{ELEC,r}$ is the change in the price of electricity $ELEC$.

$$\hat{c}_{i,r}^{E} = \left(\beta_{i,r}^{E} (\hat{c}_{i,r}^{FF})^{1-\sigma^E} + (1-\beta_{i,r}^{E})(\hat{P}_{ELEC,r})^{1-\sigma^E}\right)^{\frac{1}{1-\sigma^E}} \tag{13}$$

The $KLE_{i,r}$ nest combines the value added and the energy aggregates with the elasticity of substitution σ^{KLE}. The change in its per-unit cost index is denoted by $\hat{c}_{i,r}^{KLE}$. $\beta_{i,r}^{KLE}$ is the value share of value added in the baseline.

$$\hat{c}_{i,r}^{KLE} = \left(\beta_{i,r}^{KLE} (\hat{c}_{i,r}^{KL})^{1-\sigma^{KLE}} + (1-\beta_{i,r}^{KLE})(\hat{c}_{i,r}^{E})^{1-\sigma^{KLE}}\right)^{\frac{1}{1-\sigma^{KLE}}} \tag{14}$$

Non-energy intermediate good inputs are combined in the $Z_{i,r}$ nest by using a Leontief function. Thus, the change in the corresponding price index $\hat{c}^{Z}_{i,r}$ is a weighted average of their prices. The weights are given by the corresponding value shares $\beta^{Z}_{j,i,r}$. $[Z]$ symbolizes the set of all non-energy (intermediate) goods, i.e., all goods except energy goods and the investment good $INVS$.

$$\hat{c}^{Z}_{i,r} = \sum_{j \in [Z]} \beta^{Z}_{j,i,r} \hat{P}_{j,r} \tag{15}$$

The change in the per-unit input costs $\hat{c}_{i,r}$ is expressed as equation (16), where $\beta^{KLEM}_{i,r}$ is the value share of the $KLE_{i,r}$ aggregate, and σ^{KLEM} is the elasticity of substitution.

$$\hat{c}_{i,r} = \left(\beta^{KLEM}_{i,r} (\hat{c}^{KLE}_{i,r})^{1-\sigma^{KLEM}} + (1 - \beta^{KLEM}_{i,r})(\hat{c}^{Z}_{i,r})^{1-\sigma^{KLEM}} \right)^{\frac{1}{1-\sigma^{KLEM}}} \tag{16}$$

5.3.2 Demand functions

The demand for intermediate inputs and primary factors is split into several per-unit demand functions. The change in the demand for capital within the value added nest, for instance, is denoted by $\hat{d}^{KL,K}_{i,r}$ and depends on the relationship between the changes in the cost index of the value added aggregate $\hat{c}^{KL}_{i,r}$ and the rental rate of capital $\hat{P}^{K}_{r}$.

$$\hat{d}^{KL,K}_{i,r} = \frac{\hat{c}^{KL}_{i,r}}{\hat{P}^{K}_{r}} \tag{17}$$

Demand for labor by the $KL_{i,r}$ nest $\hat{d}^{KL,L}_{i,r}$ can be expressed analogously.

$$\hat{d}^{KL,L}_{i,r} = \frac{\hat{c}^{KL}_{i,r}}{\hat{P}^{L}_{r}} \tag{18}$$

The change in the demand for fossil fuel j by the fossil fuel nest, $\hat{d}^{FF,i}_{j,i,r}$, is also derived from a Cobb-Douglas function.

$$\hat{d}^{FF,i}_{j,i,r} = \frac{\hat{c}^{FF}_{i,r}}{\hat{P}_{j,r}} \ \forall j \in [FF] \tag{19}$$

Likewise, the change in demand for the fossil fuel aggregate by the energy aggregator is defined as

$$\hat{d}^{E,FF}_{i,r} = \left(\frac{\hat{c}^{E}_{i,r}}{\hat{c}^{FF}_{i,r}} \right)^{\sigma^{E}} \tag{20}$$

The following equation defines the change in the demand for electricity by the energy aggregator:

$$\hat{d}_{i,r}^{E,ELEC} = \left(\frac{\hat{c}_{i,r}^{E}}{\hat{P}_{ELEC,r}} \right)^{\sigma^{E}} \tag{21}$$

Correspondingly, the change in the demand for value added in the $KLE_{i,r}$ nest reads

$$\hat{d}_{i,r}^{KLE,KL} = \left(\frac{\hat{c}_{i,r}^{KLE}}{\hat{c}_{i,r}^{KL}} \right)^{\sigma^{KLE}} \tag{22}$$

and the change in the demand for the energy in the $KLE_{i,r}$ nest reads

$$\hat{d}_{i,r}^{KLE,E} = \left(\frac{\hat{c}_{i,r}^{KLE}}{\hat{c}_{i,r}^{E}} \right)^{\sigma^{KLE}} \tag{23}$$

The demand for good j (including $SAND$) by the aggregator of non-energy intermediates is derived from a Leontief function and thus remains unchanged in the counterfactual scenario.

$$\hat{d}_{j,i,r}^{Z,j} = 1 \; \forall j \in [Z] \tag{24}$$

Equations (25) and (26) show the changes in the demand for the $KLE_{i,r}$ aggregate ($\hat{d}_{i,r}^{KLEM,KLE}$) and the non-energy intermediate aggregate ($\hat{d}_{i,r}^{KLEM,Z}$), respectively.

$$\hat{d}_{i,r}^{KLEM,KLE} = \left(\frac{\hat{c}_{i,r}^{KLEM}}{\hat{c}_{i,r}^{KLE}} \right)^{\sigma^{KLEM}} \tag{25}$$

$$\hat{d}_{i,r}^{KLEM,Z} = \left(\frac{\hat{c}_{i,r}^{KLEM}}{\hat{c}_{i,r}^{Z}} \right)^{\sigma^{KLEM}} \tag{26}$$

Equation (27) defines the change in demand for intermediate input j by sector i in r, $\hat{Z}_{j,i,r}$. Here, we distinguish between three types of goods: fossil fuels $[FF]$, electricity $ELEC$, and non-energy intermediates $[Z]$ including $SAND$.

$$\hat{Z}_{j,i,r} = \begin{cases} \frac{\hat{x}_{i,r}}{\hat{c}_{i,r}} \cdot \hat{d}_{i,r}^{KLEM,KLE} \cdot \hat{d}_{i,r}^{KLE,E} \cdot \hat{d}_{i,r}^{E,FF} \cdot \hat{d}_{j,i,r}^{FF,i} & \text{if } j \in [FF] \\ \frac{\hat{x}_{i,r}}{\hat{c}_{i,r}} \cdot \hat{d}_{i,r}^{KLEM,KLE} \cdot \hat{d}_{i,r}^{KLE,E} \cdot \hat{d}_{i,r}^{E,ELEC} & \text{if } j = ELEC \\ \frac{\hat{x}_{i,r}}{\hat{c}_{i,r}} \cdot \hat{d}_{i,r}^{KLEM,Z} \cdot \hat{d}_{j,i,r}^{Z,j} & \text{if } j \in [Z] \end{cases} \tag{27}$$

Sector i's change in the demand for capital is expressed as follows:

$$\hat{K}_{i,r} = \frac{\hat{x}_{i,r}}{\hat{c}_{i,r}} \cdot \hat{d}_{i,r}^{KLEM,KLE} \cdot \hat{d}_{i,r}^{KLE,KL} \cdot \hat{d}_{i,r}^{KL,K} \tag{28}$$

Likewise, sector i's change in the demand for labor reads

$$\hat{L}_{i,r} = \frac{\hat{x}_{i,r}}{\hat{c}_{i,r}} \cdot \hat{d}_{i,r}^{KLEM,KLE} \cdot \hat{d}_{i,r}^{KLE,KL} \cdot \hat{d}_{i,r}^{KL,L} \tag{29}$$

5.4 Trade

This subsection considers international trade based on the theory of Eaton and Kortum (2002) and the implementations by Caliendo and Parro (2015) and Pothen and Hübler (2018). Equation (30) represents the change in the price index of sector i in region s, $\hat{P}_{i,s}$, between the baseline and the counterfactual scenario; it depends on the changes in per-unit costs ($\hat{c}_{i,r}$) and observable trade costs ($\hat{\tau}^t_{i,r,s}$). The baseline trade share ($\pi_{i,r,s}$) indicates the importance of changes in per-unit input cost or trade cost changes in region r for the price in region s. If region r is an important supplier of region s in the baseline, an increase in input or trade costs will have a large effect on s's price index in the counterfactual scenario. The absolute productivity ($\hat{T}_{i,r}$) represents a sector's efficiency of converting the input bundle into the output. It does not, however, appear in equation (30) because it does not change between the baseline and the counterfactual scenario ($\hat{T}_{i,r} = 1$).

$$\hat{P}_{i,s} = \sum_r \pi_{i,r,s} \left(\hat{c}_{i,r} \cdot \hat{\tau}^t_{i,r,s}\right)^{-\theta_i} \tag{30}$$

Let $\pi'_{i,r,s}$ denote the trade share, i.e., the fraction of good i that s purchases from r, in the counterfactual scenario. $\pi'_{i,r,s}$ can be written as a function that increases with the price index ($\hat{P}_{i,s}$) and decreases with the per-unit production costs of i in r ($\hat{c}_{i,r}$) multiplied by the (observable) trade costs of shipping good i from r to s ($\hat{\tau}^t_{i,r,s}$), where the arguments are measured in terms of changes:

$$\pi'_{i,r,s} = \pi_{i,r,s} \left(\frac{\hat{P}_{i,s}}{\hat{c}_{i,r} \cdot \hat{\tau}^t_{i,r,s}}\right)^{\theta_i} \tag{31}$$

Similarly, the change in the observable trade costs ($\hat{\tau}^t_{i,r,s}$) is driven by the endogenous changes in transport costs and, in the case of $SAND$, the tax or tariff under examination.

$$\hat{\tau}^t_{i,r,s} = \frac{(1+\tau^{m'}_{i,r,s})(1+\psi_{i,r,s}P^{ITR'})(1-\tau^{e'}_{i,r,s}+\tau^{o'}_{i,r})}{(1+\tau^{m}_{i,r,s})(1+\psi_{i,r,s}P^{ITR})(1-\tau^{e}_{i,r,s}+\tau^{o}_{i,r})} \tag{32}$$

The observable trade costs consist of four components. The first is the import tariff ($\tau^m_{i,r,s}$), which can change in the case of $SAND$ but remains constant in other sectors. The second are the transport costs, which, in turn, consist of the constant input of international transport services per unit of good i shipped from r to s ($\psi_{i,r,s}$) and the endogenous price of international transport services (P^{ITR}). The third is the export tariff $\tau^e_{i,r,s}$, which can also change in the case of $SAND$. The fourth is the output tax on $SAND$ ($\tau^o_{i,r}$), which equals zero in the baseline.

5.5 Transportation

International transport services are assumed to be a global Cobb-Douglas aggregate of inputs from transport sectors in all regions r. The change in their price $\hat{P}^{ITR}$ hence depends only on price changes of regional transport services, $\hat{P}_{TRNS,r}$, and the corresponding value shares ζ_r.

$$\hat{P}^{ITR} = \prod_r (\hat{P}_{TRNS,r})^{\zeta_r} \tag{33}$$

5.6 Markets

5.6.1 Transportation market clearing

Referring to the previous subsection, the following equation represents the market clearing condition for international (global) transportation services in the counterfactual scenario, where $Q^{ITR'}$ denotes the supply of international transport services.

$$Q^{ITR'} = \sum_{i,r,s} \psi_{i,r,s} \frac{(1 - \tau^{e'}_{i,r,s} + \tau^{s'}_{i,r,s})}{\tau^{t'}_{i,r,s}} \pi^{'}_{i,r,s} D^{'}_{i,s} \tag{34}$$

5.6.2 Goods market clearing

Market clearance is required in all production sectors i (including $SAND$ and $INVS$). For this purpose, let us write the counterfactual sales of sector i in region r ($X^{\prime}_{i,r}$) as a positive function of the expenditures on good i in all regions s ($D^{'}_{i,s}$), the fraction of these expenditures purchased from r ($\pi^{'}_{i,r,s}$) and a negative function of the (observable) trade costs ($\tau^{t'}_{i,r,s}$) between r and s. In the transportation sector $TRNS$, the sales to the international transport services ($\zeta_r Q^{ITR'} P^{ITR'}$) are added to the right-hand side of the following equation.

$$X'_{i,r} = \sum_s \pi'_{i,r,s} \frac{D'_{i,s}}{\tau^{t'}_{i,r,s}} \tag{35}$$

Furthermore, the expenditures on good i in region s must equal the sum of the expenditures on consumption ($C'_{i,s}$) and intermediate good inputs ($Z'_{i,j,s}$):

$$D'_{i,s} = P'_{i,s} \left(C'_{i,s} + \sum_j Z'_{i,j,s} \right) \tag{36}$$

5.6.3 Factor market clearing

A well-defined model solution requires clearance of all factor markets as well. The following capital market clearing condition equates the region-specific, exogenous and constant capital endowment ($\bar{K}_r$) with the endogenous counterfactual demand for capital ($K'_{i,r}$) by all sectors i in region r. This equilibrium condition determines the rental rate of capital ($P^{K'}_r$), where capital includes natural resources.

$$\bar{K}_r = \sum_i K'_{i,r} \tag{37}$$

Finally, the wage rate ($P^{L'}_r$) is determined by the corresponding labor market clearing condition:

$$\bar{L}_r = \sum_i L'_{i,r} \tag{38}$$

5.7 Income

The income (value) of the representative consumers of region s in the counterfactual scenario (Y'_s) consists of capital income ($P^{K'}_s \bar{K}_s$), labor income ($P^{L'}_s \bar{L}_s$), redistributed tax revenues (Ξ'_s) and the current account deficit (Δ_s).

$$Y'_s = P^{K'}_s \bar{K}_s + P^{L'}_s \bar{L}_s + \Xi'_s + \Delta_s \tag{39}$$

This income balance condition must hold in each model equilibrium. Whereas Δ_s remains unchanged across scenarios, the values of the other income sources change endogenously.

The corresponding income value in the baseline (Y_s) is given so that the income change $\hat{Y}_s$ can be derived. Based on that, the welfare change between the counterfactual scenario and the baseline can be expressed as

$$\hat{w}_s = \frac{\hat{Y}_s}{\hat{c}_r^C} \tag{40}$$

where $\hat{c}_r^C$ denotes the change in the true-cost-of-living index, i.e., the price of the optimal consumption bundle derived from the CES utility function in figure A1.

5.8 Policies

This subsection rephrases the policies discussed in section 4.5 in a mathematical form. All changes in the model solution are driven by adding a positive sand tax to the price of sand (and gravel) $\tau^{S'}$ in the counterfactual scenario. Depending on the policy scenario, this tax is imposed on imports (to Singapore), exports (of the Southeast Asian suppliers) or total output (total sales of the Southeast Asian suppliers) of $SAND$. The corresponding ad valorem tax (tariff) rates are derived as explained in section 4.5.

Equation (41) expresses Singapore's ad-valorem import tariff on sand in the counterfactual scenario, $\tau^{m'}_{SAND,r,s}$. The division of $\tau^{S'}$ by the counterfactual sand price measured relative to the baseline price ($\hat{P}_{SAND,r}$) eliminates monetary price effects. S_r denotes the amount of sand (and gravel) extracted in r; $X_{SAND,r}$ is the monetary value of sand sales; and $\frac{S_r}{X_{SAND,r}}$ is the resulting sand intensity that is constant across scenarios. The tariff revenues accrue to the representative consumer of the importing region s, i.e., Singapore (SGP), as a lump sum.

$$\tau^{m'}_{SAND,r,s} = \begin{cases} \frac{\tau^{S'}}{\hat{P}_{SAND,r}} \cdot \frac{S_r}{X_{SAND,r}} & \text{if } r \neq s \ \wedge \ s = SGP \\ \textit{not applicable} & \text{otherwise} \end{cases} \tag{41}$$

The export tariff in the counter-factual scenario ($-\tau^{e'}_{SAND,r,s}$) is computed similarly. The minus sign is necessary because, following the GTAP approach, we implement export subsidies rather than export tariffs. Notably, the revenues from export tariffs are redistributed to the representative consumer of the exporting region $r \in [SX]$ as a lump sum, where $[SX]$ symbolizes the subset of sand exporters $\{KHM, MMR, MYS, PHL, VNM\}$.

$$-\tau^{e'}_{SAND,r,s} = \begin{cases} \frac{\tau^{S'}}{\hat{P}_{SAND,r}} \cdot \frac{S_r}{X_{SAND,r}} & \text{if } r \neq s \wedge \ r \in [SX] \\ \textit{not applicable} & \text{otherwise} \end{cases} \tag{42}$$

The (output) sales tax on sand in the counter-factual scenario ($\tau^{o'}_{SAND,r}$) is computed accordingly.

$$\tau^{o'}_{SAND,r} = \begin{cases} \frac{\tau^{S'}}{\hat{P}_{SAND,r}} \cdot \frac{S_r}{X_{SAND,r}} & \text{if } \; r \in [SX] \\ \textit{not applicable} & \text{otherwise} \end{cases} \tag{43}$$

Unlike the tariff imposed on exports, it is levied on all sales of sand including those to domestic consumers and firms; i.e., the tax base is broader. Revenues are redistributed to the representative consumer of the sand-extracting country r as a lump sum.

These policy definitions complete the model description.

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