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Abstract

Energy security ranks high on the policy agenda of many countries. To improve on energy security, governments undertake regulatory measures for promoting renewable energy, increasing energy efficiency, or curbing carbon dioxide emissions. The impacts of such measures on energy security are typically monitored by means of so-called energy security indicators. In this paper, we show that the common use of wide-spread energy security indicators falls short of providing a meaningful metric. Regulatory measures to improve on energy security trigger ambiguous effects across energy security indicators. We conclude that a major pitfall of energy security indicators is the lack of a rigorous microeconomic foundation.

Keywords: energy security, energy security indicators, computable general equilibrium analysis

JEL classifications: D58, Q48

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1 Introduction

Energy security ranks high on the policy agenda of many countries. Governments use the notion of energy security as a rationale for justifying massive intervention into energy markets. More specifically, policy makers launch programs to (i) increase domestic renewable energy production, (ii) promote energy efficiency, and (iii) reduce CO_2 emissions from fossil fuel combustion.

As a prime example, the European Union (EU) perceives its EU Energy Security and Solidarity Action Plan (European Commission, 2008) as an important step to increase energy security for its member states. It embraces energy efficiency because "consuming less through energy efficiency is the most durable way to reduce dependence on fossil fuels and imports". Renewable energies are appraised because its "development […] has to be seen as the EU's greatest potential source of indigenous energy". Last but not least, the EU also justifies ambitious CO_2 emission reduction targets not only as a contribution in the battle against anthropogenic climate change but also as an effective instrument to improve on energy security because "in the long term, the Union's energy security is inseparable from […] its need to move to a competitive, low-carbon economy which reduces the use of imported fossil fuels." (European Commission, 2014).

In EU energy policy, energy security is considered predominantly as a supply-side phenomenon hinging on the magnitude of energy imports as well as the diversity of energy sources and energy suppliers.[1] In this context the following four energy security indicators are of particular importance: (i) primary energy intensity (EI) as the ratio of total physical primary energy supply over gross domestic product (GDP), (ii) net-import dependency (NID) calculated as the sum of the shares of positive net-imports for each fossil

[1] The European Commission argues that the "Union's prosperity and security hinges on a stable and abundant supply of energy." (European Commission, 2014). Against this background, EU energy policy is intended to break the cycle of increasing energy consumption and increasing energy imports while fostering diversity of energy sources and diversity of suppliers (European Commission, 2008).

primary energy carrier in total primary energy supply, (iii) primary energy carrier dependency (PECD) as the squared sum of the shares of total supply of a specific primary energy carrier in total primary energy supply, and (iv) supplier dependency (SD) measuring the concentration of supplier-specific net positive import shares in total net imports.

We show that these indicators can create mutually inconsistent results on how regulatory measures affect the level of energy security. Among our three principal policy measures considered[2] – renewable energy promotion, energy efficiency improvements, and CO_2 emission reduction – only energy efficiency improvements advance all the indicators throughout; renewable energy promotion and CO_2 emission reduction on the other hand yield ambiguous results.[3] If one conceives energy security as a multi-dimensional problem reflected in different indicators, energy efficiency improvements could be viewed as the only robust strategy, at least according to the four metrics used in our analysis (see also Sovacool and Saunders (2014) who argue that energy security is all about managing conflicts and commonalities between the different dimensions of energy security).

Our analysis furthermore shows that there is no clear cost-effectiveness ranking across policy measures: As we quantify the economic cost to improve energy security, none of the three policies under consideration turns out to be a dominating least-cost strategy.[4] Our results which are based on simulations

[2] There are various other options to increase energy security which we do not consider in our analysis as we focus on the EU’s three primary strategies. Examples include the provision of physical storage for gas or oil, backup fuels for electricity generation, or demand side management (Oxera, 2007; PÖYRY, 2010).

[3] Energy security is not the only policy objective which is addressed by the three principal policy measures considered in this paper. They are also directed to other policy objectives, first of all to the mitigation of climate change but also to the creation of green jobs and green growth. However, EU policy makers make a strong case for each of these policies in order to improve energy security.

[4] A dominant least-cost policy would improve each of the four energy security indicators investigated at lower cost than all other polices.

with a large-scale computable general equilibrium (CGE) model of global economic activity highlight the pitfall of the energy security debate. From a descriptive positive perspective, the heterogeneity in energy security indicators may lead to contradicting conclusions on the desirability of policy measures intended for improvements in energy security: An issue that cannot be measured is difficult to improve. The fundamental shortcoming of using common energy security indicators is their lack of a rigorous microeconomic foundation.[5] Each indicator is composed differently and just measures energy security on an ordinal level. Thus, it is not possible to perform a meaningful economic comparison across the different indicators. There is no money-metric translation of changes in energy security indicators that could make these amenable for a rigorous economic cost-effectiveness assessment.[6]

In essence, our analysis stresses the need for a rigorous welfare foundation of the energy security concepts. The notion of energy security must be linked to the existence of market failures where the benefits of reducing negative energy (security) market externalities can be monetized in standard welfare metrics, e.g. in terms of economic surplus or Hicksian equivalent variation in income.

Our paper contributes to the small but growing literature that provides a critical perspective on the use of energy security indicators for governing energy security policies.[7] In this literature it is argued that energy security indicators suffer from at least one of the following limitations. First, various indicators – being supply-oriented – undervalue the importance of the demand side (Jansen and Seebregts, 2010; Sovacool,

[5] Such a framework is based on economic choices of rationally behaving market agents that maximize their economic net benefits thereby trading off marginal benefits of their economic decisions with marginal costs.

[6] This is apparently quite different from cost-effectiveness analysis of alternative climate policy measures where we can refer to a single unambiguous indicator, i.e., the level of CO_2 emissions.

[7] Studies that develop and apply energy security indicators for governing energy security policies include Costantini et al. (2007), Gnansounou (2008), Le Coq and Paltseva (2009), Jansen and Seebregts (2010), Lefèvre (2010), Löschel et al. (2010), Cohen, Joutz, and Loungani (2011), Sovacool et al. (2011), Sovacool (2013), Frondel and Schmidt (2014), and Yao and Chang (2014).

2013; Gracceva and Zeniewski, 2014). Second, indicators are limited in assessing specific energy system's responses to exogenous future shocks as they carry only condensed proxy information (Cherp and Jewell, 2011; Gracceva and Zeniewski, 2014). Third, energy security indicators do not provide information on economic costs and benefits of alternative levels of energy security (Gracceva and Zeniewski, 2014). Fourth, the multifacetedness of the energy security notion gives rise for multiple indicators but then faces inherent difficulties of a meaningful aggregation (Böhringer and Jochem, 2007; Kruyt et al., 2009; Frondel and Schmidt, 2014).[8] Our paper addresses the two latter shortcomings. More generally, we argue that scientific research hardly alludes to the major pitfall for the economic assessments of energy security policies: the missing microeconomic foundation of the energy security notion and consequently the lack of a viable energy security indicator.

The remainder of this paper is as follows. In section 2, we present and discuss the four indicators that we use to quantify energy security. In section 3, we describe the CGE model of global economic activity which we use to quantify the impacts of alternative energy security policies undertaken by the EU. In section 4, we discuss the results of our CGE analysis where we investigate how energy security policies affect energy security indicators and economic performance. In section 5, we summarize and conclude.

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[8] The meaningful construction of a composite indicator for energy security requires sound methods for normalization, weighting, and aggregation of the different contributing indicators (Böhringer and Jochem, 2007). In practice, however, composite indicators are mostly constructed ad hoc (Freudenberg, 2003), particularly with respect to weighting procedures. Exceptions which go for more rigorous weighting procedures include Ren and Sovacool (2014, 2015) who apply fuzzy set theory to incorporate uncertainty.

2 Energy security indicators

The literature on energy security draws on a large number of indicators whose comprehensive discussion would go well beyond the scope of this paper.[9] Instead, we focus on four indicators which capture dependency on (i) primary energy, (ii) foreign primary energy supply, (iii) primary energy carriers, and (iv) foreign primary energy suppliers. These indicators are not only widely used in the literature but also have strong appeal in the context of EU energy policy intending to break the cycle of increasing energy and import dependency as well as to increase diversity of energy sources and suppliers (European Commission, 2008).

2.1 Dependency on primary energy

Primary energy dependency refers to the degree to which economic activities depend on primary energy as input. The larger the primary energy input requirements of production and consumption activities are, the larger the adjustment costs for the economy due to price shocks and physical supply shortfalls are supposed to be (Kruyt et al., 2009). A commonly used indicator is the primary energy intensity (EI) of GDP which is calculated as the ratio of total physical primary energy supply (TPES) over GDP.

$$EI = \frac{TPES}{GDP} \qquad (1)$$

However, the indicator is subject to various conceptional and measurement problems affecting either the size of the numerator or the denominator. First, since energy statistics typically do not account for indirect primary energy supply (i.e., primary energy embodied in non-energy imports), primary energy intensity of GDP underestimates the economy’s dependency on primary energy. In addition, since improvements in energy intensity can result from substitution of domestic production of goods for imports (i.e., substitution of direct energy consumption for embodied energy consumption) rather than from diffusion of energy

[9] For reviews on energy security indicators see, for instance, Kruyt et al. (2009), Löschel et al. (2010), or Sovacool and Mukherjee (2011).

savings technologies, the interpretation of energy intensity improvements can be ambiguous (Gnansounou, 2008). Second, the indicator is not increasing in the riskiness of TPES. This is because in the calculation of TPES, supply of each energy carrier is commonly treated as being equally exposed to supply disruption risks. Incorporating carrier-specific risks would require a weighting of the different fuels in the calculation of TPES according to their specific risk. Third, as it comes to cross-country comparisons of energy intensity, the choice of the currency conversion rate – market exchange rates (MER) versus purchasing power parities (PPP) – can substantially alter the indicator value. Since the actual purchasing power of GDP drives the economy’s energy use, PPP are commonly used for converting currencies (Samuelson, 2014). However, since PPP tend to underestimate (overestimate) GDP in advanced (developing) countries, energy security using PPP as currency conversion rate is likely to be smaller (larger) in reality than indicated by the indicator (Suehiro, 2008). Fourth and finally, there are other factors than TPES affecting macroeconomic adjustment which are not captured in the indicator. For instance, the existence of wage rigidities results in increased unemployment after an energy price shock (Bohi and Toman, 1993). In presence of wage rigidities, energy intensity would underestimate the economy’s sensitivity to primary energy disruptions.

2.2 Dependency on external primary energy supply

Dependency on external (foreign) primary energy supply provides insights about the domestic economy's exposure to price and quantity risks in global primary energy markets. Since global markets for renewables are currently not existent and supply with nuclear fuels is considered as reliable, dependency on external primary energy refers to dependency on external fossil primary energy supply, i.e., supply of coal, crude oil and natural gas. Higher levels of fossil primary energy imports are considered as being more risky (Bhattacharyya, 2011). The crucial assumption behind this argument is that while governments can effectively control domestic fossil primary energy supply they do not have control over external fossil primary energy supply. The net positive import share of energy consumption – referred to as net import dependency (NID) – is commonly used as an indicator for fossil primary energy import dependency. The logic behind the use of positive net-imports rather than (gross) imports is that shortfalls in energy imports can be compensated for by adjustments in energy exports (Le Coq and Paltseva, 2009). NID is calculated as the sum of the shares of positive physical net-imports for each fossil primary energy carrier ff in total physical primary energy supply (TPES). M_{ff} stands for total imports of fossil primary energy ff while X_{ff} represents total exports of fossil primary energy *ff*.

$$NID = \sum_{ff} \frac{max\left(0, M_{ff} - X_{ff}\right)}{TPES} \tag{2}$$

Since the calculation of NID requires data for consumption and international trade flows of primary energy, the same caveats with respect to embodied energy and the fuel's riskiness apply as for energy intensity of GDP. Considering net-imports rather than imports is also problematic. If we assume that a shortfall in energy imports can be compensated for by energy exports we necessarily have to account for chain effects that an energy security problem in one country will have on energy imports of its trading partners and the responses of these countries. In short, redirecting energy exports to domestic consumption can aggravate rather than attenuate the energy security problem.

2.3 Dependency on primary energy carriers

Dependency on primary energy carriers describes the reliance of economic activities on specific primary energy carriers (i.e. coal, natural gas, crude oil, nuclear energy, and renewables). In the light of economy-wide limited short-term substitution possibilities, high dependency on a single primary energy carrier implies high exposure of the domestic economy to price and quantity (supply) risks of a specific energy carrier – this situation is generally considered as highly risky (Bhattacharyya, 2011). Concentration or diversity indices are used to measure this dimension of dependency. A wide-spread indicator here is the Herfindahl-Hirschman concentration index applied to the primary energy mix of the economy's total primary energy consumption.[10] Primary energy carrier dependency (PECD) is calculated as the squared sum of the shares of total physical supply of primary energy carrier f (S_f) in total physical primary energy supply (TPES). Larger values of the indicator signal a more concentrated primary energy carrier mix towards some particular primary energy carriers, which in turn implies higher primary energy carrier dependency.

$$PECD = \sum_{f} \left(\frac{S_f}{TPES}\right)^2 \tag{3}$$

Stirling (2010) criticizes the measurement of fuel mix diversity with Herfindahl-Hirschman based indices, since disparity between the different primary energy carriers in the supply mix is neglected. Disparity is a measure for the degree to which different primary energy supply options can be distinguished. In general, inclusion of more disparate primary energy carriers into the primary energy mix increases energy security. For instance, since crude oil and natural gas are closer substitutes than nuclear energy and crude oil, disparity between the former is lower than between the latter

2.4 Dependency on external primary energy suppliers

Dependency on external primary energy suppliers refers to the reliance of the domestic economy on single external suppliers.[11] Again, only fossil primary energy suppliers are taken into consideration as the supply of renewables and nuclear energy is not considered as critical. The more the domestic economy's activities depend on single external fossil primary energy suppliers, the higher is the exposure of price and quantity

[10] An alternative to the Herfindahl-Hirschman concentration index would be the Shannon-Weaver index, which measures diversity rather than concentration. In contrast to the latter, the Herfindahl-Hirschman concentration index puts relatively more weight on the impact of larger shares of primary energy carriers in the fuel mix (Frondel and Schmidt, 2014; Le Coq and Paltseva, 2009).

[11] Domestic suppliers are excluded since it is assumed that control of domestic suppliers is far less difficult than control of external suppliers.

risks associated with these suppliers. Accordingly, diversity of sourcing options is widely seen as a key strategy for avoiding energy supply breakdowns (Kleindorfer and Saad, 2005). Supplier dependency (SD) for fossil primary energy carrier ff is measured by means of a carrier specific Herfindahl-Hirschman concentration index. The index measures the concentration of supplier specific net positive import shares in total net positive imports:[12]

$$SD_{ff} = \sum_i a_i^{HHI} \left(\frac{max\left(0, M_{i,ff} - X_{i,ff}\right)}{\sum_i max\left(0, M_{i,ff} - X_{i,ff}\right)} \right)^2 \qquad (4)$$

Hereby, $M_{i,ff}$ represents fossil primary energy imports coming from supplier i while $X_{i,ff}$ denotes EU's fossil primary energy exports to country i. Furthermore, to account for political risk of suppliers, supplier specific risk factors a_i^{HHI} are included. These risk factors scale up the weight of more risky suppliers in the calculation of the indicator value. Larger values signal a more concentrated supplier-mix and, therefore, imply higher dependency on some particular suppliers.

Since we are interested in the supplier mix of total external primary energy supply, we aggregate the three carrier-specific supplier dependency indicators to one aggregated fossil primary energy supplier dependency indicator. The computation of the composite supplier dependency (SD) follows Frondel and Schmidt (2014) by using a weighted average of the carrier specific concentration indices. The weights for the individual indices are the carriers' net positive imports relative to total net positive imports of fossil fuels.

$$SD = \sum_{ff} \frac{\sum_i max\left(0, M_{i,ff} - X_{i,ff}\right)}{\sum_{ff} \sum_i max\left(0, M_{i,ff} - X_{i,ff}\right)} SD_{ff} \qquad (5)$$

The indicator can be criticized for neglecting two important aspects: transport risk and fungibility of suppliers (Le Coq and Paltseva, 2009). Transport risk refers to the risk of energy supply being disrupted

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[12] In the case of crude oil OPEC is considered as one supplier.

on the path from the supplier to the consumer by, for instance, a third party having a political conflict with either the supplier or the customer. The supplier then would be more insecure if its primary energy is transported through the thirds party's territory.[13] Fungibility refers to the ease of switching between suppliers. It is largely determined by how the energy is transported. For instance, pipeline supply of natural gas is less fungible in the short run than liquefied natural gas (LNG) supply. Hence, dependency on pipeline gas suppliers is higher than dependency on LNG suppliers.

3 Computable general equilibrium analysis of energy security policies

Governments all over the world apply a myriad of policy instruments to foster energy security. The basic reasoning is that increased energy security reduces the adverse impacts of potential energy supply disruptions for the economy. On the grounds of economic efficiency, a rationale policy should trade off the cost of increasing energy security with its benefits. The quantification of economic trade-offs calls for the use of numerical models to assess systematically the interference of the many forces that interact in the economy. Among numerical approaches, CGE models have become a standard tool for assessing the economy-wide impacts of policy interventions. CGE models build upon general equilibrium theory that combines behavioral assumptions on rational economic agents with the analysis of equilibrium conditions (Cardenete et al., 2012). They provide counterfactual ex-ante comparisons, assessing the outcomes with a reform in place with what would have happened had the reform not been undertaken. The main virtue of the CGE approach is its comprehensive microeconomic representation of price-dependent market interactions. Due to the rigorous microeconomic foundation, CGE models allow for normative (welfare) rankings of alternative policy reforms compared to the status-quo. However conventional CGE models of energy-economy interactions have a limited representation of the energy system. Energy transformation

[13] The Russia-Ukraine gas disputes since 2005 are one example for transport risks. These disputes between Ukrainian gas companies and their Russian gas suppliers over supplies, prices and debts threatens natural gas supplies in foremost eastern European countries being dependent on Russian natural gas which is supplied through Ukraine.

processes are characterized top-down by smooth production functions which capture local substitution (transformation) possibilities through constant elasticities of substitution (transformation). As a consequence, top-down CGE models lack detail on technological options and fundamental physical restrictions in the energy system, which may be relevant in the assessment of energy policy proposals. To attenuate this shortcoming with respect to our analysis of energy security, we adopt a hybrid top-down bottom-up model setting, where we include a bottom-up activity analysis representation of the electricity system in an otherwise conventional (top-down) multi-sector multi region CGE model of the global economy (Böhringer and Rutherford, 2010). Below we provide a non-technical summary of the model and its parametrization. Appendix A features an algebraic exposition of the model structure. Appendix B provides a graphical exposition of the nesting structure of flexible functional forms used to capture production technologies and consumer preferences.

3.1 Non-technical model summary

In each region a representative agent receives income from three primary factors: labor, capital, and fossil primary energy resources (i.e., coal, gas and crude oil). Labor and capital are intersectorally mobile within a region but immobile between regions. Fossil primary energy resources are specific to fossil primary energy production sectors in each region.

Production of commodities other than fossil primary energy is captured by three-level constant elasticity of substitution (CES) cost functions describing the price-responsive use of capital, labor, energy, and material in production. At the top level, a CES composite of intermediate material demands trades off with an aggregate of energy, capital, and labor subject to a constant elasticity of substitution. At the second level, a CES function describes the substitution possibilities between demand for the energy aggregate and a value-added composite of labor and capital. At the third level, capital and labor substitution possibilities within the value-added composite are captured by a CES function whereas different energy inputs (coal, gas, refined oil, and electricity) enter the energy composite subject to a constant elasticity of substitution.

In the production of fossil primary energy (crude oil, natural gas, and coal), all inputs, except for the sector-specific fossil primary energy resource, are aggregated in fixed proportions. This aggregate trades off with the sector-specific fossil primary energy resource at a constant elasticity of substitution. The substitution elasticity between the specific factor and the Leontief composite at the top is calibrated in consistency with an exogenously given supply elasticity of fossil primary energy (Rutherford, 2002).

Given the paramount importance of the electricity sector as a major consumer of primary energy, the standard representation of electricity generation through a single CES production (cost) function is replaced by a bottom-up activity analysis characterization where several discrete generation technologies compete to supply electricity to regional markets.[14] The price of electricity then is determined by the production costs of the marginal supplier. Electricity generation technologies respond to changes in electricity prices according to technology-specific supply elasticities. In addition, lower and upper bounds on production capacities can set explicit limits to the decline and the expansion of technologies.

Final consumption demand in each region is determined by the representative agent who maximizes utility subject to a budget constraint with fixed investment (i.e., a given demand for the savings good) and exogenous government provision of public goods and services. Total income of the representative household consists of net factor income and tax revenues. Consumption demand of the representative agent is given as a CES composite that combines consumption of non-electric energy and composite of other consumption goods. Substitution patterns within the consumption bundle are reflected through a CES function which has the same structure as the production of commodities other than fossil primary energy.

[14] The following electricity generation technologies are included into the model: coal-fired power plants, gas-fired power plants, oil-fired power plants, nuclear power plants, and renewables. Renewables include solar electricity generation, geothermal electricity generation, wind-powered electricity generation, hydroelectric generation, and other renewable electricity generation technologies.

Bilateral trade is specified following the Armington approach of product heterogeneity, domestic and foreign goods are thereby distinguished by origin (Armington, 1969). All goods used on the domestic market in intermediate and final demand correspond to a CES composite that combines the domestically produced good and the imported good from other regions differentiated by demand category (i.e., the composition of the Armington good differs across sectors and final demand components). Domestic production is split between domestic supply to the formation of the Armington good and export supply to other regions subject to a constant elasticity of transformation (CET). The balance of payment constraint, which is warranted through flexible exchange rates, incorporates the base-year trade deficit or surplus for each region.

Physical primary energy consumption is linked in fixed proportions to the use of primary energy in economic production and final demand activities, with coefficients differentiated by the carrier-specific physical energy content. Changes in primary energy consumption take place through primary energy carrier switching (inter-carrier substitution) or energy savings (either by energy-non-energy substitution or by a scale reduction of production and final demand activities). In a similar way, carbon emissions are linked to the use of carbon emitting fuels.

All the variables entering the definition of energy security indicators described in section 2 are covered in the CGE model. Hence, it is straightforward to quantify how regulatory measures affect energy security measured in terms of energy security indicators.

3.2 Data

The model builds on the GTAP data set (version 8) which includes detailed accounts of regional production, regional consumption, bilateral trade flows as well as data on physical energy consumption, physical energy trade flows, and CO_2 emissions for the base year 2007 (Badri et al., 2012). As is customary in applied general equilibrium analysis, base year data together with exogenous elasticities determine the free parameters of the functional forms. Elasticities in international trade (Armington elasticities) are directly provided by the GTAP database. Substitution elasticities between capital, labor, energy and non-energy inputs (KLEM elasticities) are taken from econometric estimates by Okagawa and Ban (2008). The elasticities of substitution in fossil primary energy production are calibrated to match exogenous estimates of fossil primary energy supply elasticities (Graham et al., 1999; Krichene, 2002; Ringlund et al., 2008).

As to sectoral and regional model resolution, the GTAP database is aggregated towards a composite data set that accounts for the specific requirements of our energy security assessment (see Table 1).

Table 1: Sectors and regions

Sectors
Energy goods
Coal, crude oil, natural gas, refined oil products, electricity
Non-energy goods
Energy-intensive industries, transport, rest of industry
Regions
OECD regions and Russia
EU27, Australia, Canada, Japan, Norway, Russia, USA, Other OECD
Non-OECD regions (excl. Russia)
Azerbaijan, Brazil, China, Colombia, India, Indonesia*, Iran*, Kazakhstan, Nigeria*, Saudi Arabia*, South Africa, Rest of Western Asia (Iraq)*, Rest of North Africa (Algeria and Libya)*, Other OPEC countries*, Other non-OPEC countries

* OPEC countries

At the sectoral level, our composite dataset includes all major primary and secondary energy carriers: coal, crude oil, natural gas, refined oil products, and electricity. The dataset furthermore distinguishes composites of energy-intensive production and transport activities. All remaining industries and services are represented through an aggregate sector (rest of industry). For the bottom-up representation of the electricity sector the aggregated GTAP data is decomposed across technologies using cost data from Blesl, Wissel, and Mayer-Spohn (2008) and technology shares from Energy Information Agency (2013).

Primary energy equivalents of electricity production from non-fossil fuels (i.e. nuclear energy and renewables) are calculated according to the physical energy content method.[15]

The regional disaggregation reflects the focus of our quantitative analysis on energy security policies undertaken by the EU. Since the principles of EU energy policy – including the notions and indicators of energy security – apply to the EU as a whole, we treat the 27 EU Member States as one composite region. To capture the EU's dependency on external energy suppliers, we include all major energy suppliers. Suppliers are considered as major suppliers if their import share is larger than 2% for at least one fossil fuel.[16] Table 2 lists these major energy suppliers to the EU for crude oil, (hard) coal, and natural gas. All OPEC countries which are not major suppliers are aggregated toward a composite OPEC region (other OPEC countries). Beyond the EU's major energy suppliers, the dataset compiled for the CGE analysis includes explicitly all major (non-energy) trading partners of the EU to reflect feedback and spillover effects from international markets.

[15] For renewables the primary energy input is assumed to be equivalent to the electricity generated while for nuclear energy a representative conversion coefficient of 33% is chosen.

[16] Import shares are calculated based on Eurostat statistics for the GTAP base year, i.e., 2007.

Table 2: Import shares of EU's major energy suppliers in 2007

Crude oil		Hard coal		Natural gas	
Russia	30.76%	Russia	22.47%	Russia	31.85%
Norway	13.94%	South Africa	18.64%	Norway	23.39%
Libya	9.04%	Australia	12.09%	Algeria	12.76%
Saudi Arabia	6.70%	Colombia	11.68%	Nigeria	3.86%
Iran	5.75%	United States	8.39%	Libya	2.52%
Kazakhstan	4.30%	Indonesia	6.49%		
Iraq	3.17%	Canada	2.81%		
Azerbaijan	2.76%				
Nigeria	2.53%				

Among energy security indicators, the supplier dependency (SD) index demands for additional information on supplier specific risk factors. Following Lefèvre (2010), information on these risk factors are taken from the Worldwide Governance Indicators (WGI) Project. The WGI project provides six composite indicators on governance performance since 1996 for more than 200 countries (Kaufmann et al., 2010). The two indicators of relevance for our energy security assessment are “Political Stability and Absence of Violence” and “Regulatory Quality”. While the former captures “the perceptions of the likelihood that the government will be destabilized or overthrown by unconstitutional or violent means” the latter reflects “perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development” (Kaufmann et al., 2010). Both indicators are reported on an annual basis and are defined over a value range between -2.5 and 2.5. Higher values thereby indicate better governance. For our analysis, we take an average of the two indicators which is scaled to the interval [1,2]: countries with the best governance performance assume an indicator value of 1 while countries with the worst performance assume a value of 2. Given the mapping of countries to the regions in our model, the country-specific and primary energy specific risk indicators are aggregated as a weighted average whereby the weights are the countries’ share in regional fossil primary energy exports (see Table C.1 in Appendix C for the region- and primary energy specific risk factors).

4 Policy scenarios and simulation results

We use the CGE model to illustrate the challenges of energy security policies based on energy security indicators. More specifically, we investigate how policies intended to increase energy security for a specific region – in our case the EU – affect energy security indicators and overall economic performance. Improvements in energy security indicators are thereby taken as an increase in energy security. While our CGE analysis abstains from valuing the benefits of energy security (such as reduced losses from energy supply disruptions) it provides a price tag to alternative regulatory measures and the associated changes in energy security indicators.

4.1 Policy scenarios

The EU is a prime example for pushing policy initiatives to foster energy security (European Commission, 2008). Principal among the initiatives are programs to (i) increase domestic renewable energy production, (ii) promote energy efficiency, and (iii) reduce CO_2 emissions from fossil fuel combustion. In our simulations we implement these programs as follows: subsidies to renewables in electricity generation for the promotion of renewables; taxes on primary energy use for improvements in energy efficiency; and carbon taxes for reducing CO_2 emissions.[17] Subsidies are financed lump-sum through the representative agent while revenues from energy and emission taxes are recycled lump-sum. To reflect increased reservations against nuclear energy in the aftermath of the Fukushima Daiichi disaster, we limit the EU-wide use of nuclear energy to the base-year level.[18] For each of the three policies, we consider a range of target levels at incremental steps. Regarding CO_2 emission reduction and energy efficiency improvements the target levels range from 0% to 30% as compared to 2007 base-year levels. Regarding renewable energy promotion, the target levels range from +0% points to +30% points of the reference share of renewables in electricity supply which is 17.4% for 2007. Table 1 summarizes the main characteristics of the three policy scenarios.

[17] Technically, we impose quotas on the use of renewables, the consumption of primary energy, and emissions which translate into endogenous taxes and subsidies.

[18] While some EU countries continue the support of nuclear energy (e.g. France, Finland, Czech Republic, Poland) other EU countries are phasing out nuclear energy (e.g. Austria, Germany, Belgium) or decided to maintain their anti-nuclear strategy (e.g. Denmark, Italy, Greece).

Table 1: Policy scenarios to foster energy security in the EU

Scenario	Basic assumptions	Target level
REN	Target share of renewables in EU electricity production (implemented via an endogenous subsidy on renewable electricity supply technologies)	17.4%-47.4%
EFF	Reduction in primary energy use from base-year levels (implemented via an endogenous tax on fossil primary energy use)	0%-30%
CO2	CO_2 emission reduction target for the EU (implemented via an endogenous tax on carbon emissions)	0%-30%

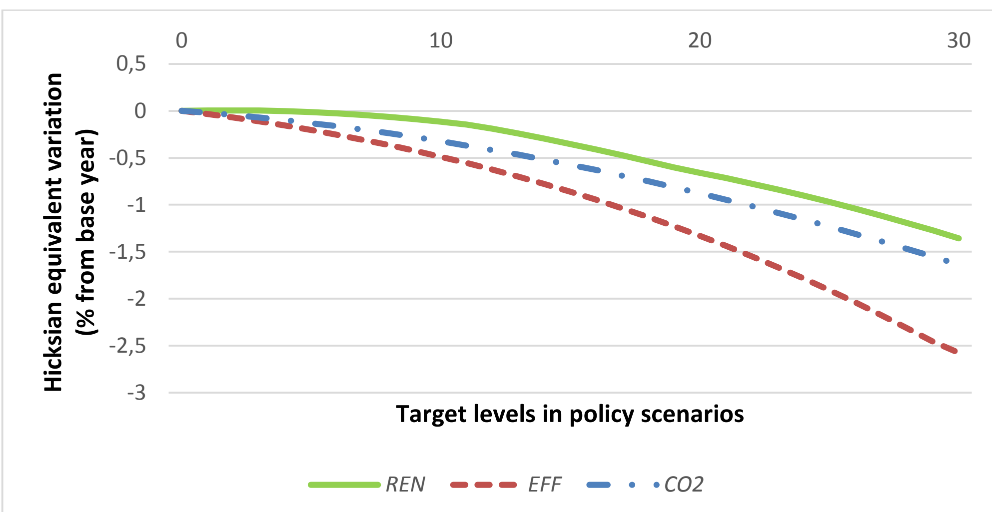
4.2 Simulation results

In the discussion of simulation results we focus on the policy-induced changes in four energy security indicators as laid out in section 2: EI – energy intensity; NID – net import dependency; PECD – primary energy carrier dependency; SD – supplier dependency. In addition, we quantify the aggregate economic impacts in terms of welfare changes. Welfare changes are reported in Hicksian equivalent variation in income. This measure denotes the amount which is necessary to add to (or subtract from) the base-year income of the representative household so that the household enjoys a utility level equal to the one in the counterfactual policy scenario on the basis of ex-ante relative prices.[19]

4.2.1 Welfare impacts of energy security policies

Figure 1 depicts the welfare impacts for the three energy security policies REN, EFF, and CO2 over the whole range of target levels.

Figure 1: Welfare effects of energy security policies



Key: REN – subsidies to renewables in electricity generation for the promotion of renewables; EFF - taxes on primary energy use for improvements in energy efficiency; CO2 - carbon taxes for reducing CO_2 emissions

[19] In our static model with fixed investment and labor supply, changes in the Hicksian equivalent variation of income directly correspond to changes in real consumption.

The main message is that all energy security policies induce economic adjustment cost which increase in the target level of the policy. This result is not surprising for two reasons. Firstly, all policies impose restrictions on energy use as compared to the unconstrained reference (base-year) situation – higher policy targets imply more stringent constraints which translate in higher economic costs as it becomes increasingly expensive to adjust production and consumption patterns. Secondly – as pointed out before – our accounting framework does not incorporate the economic benefits of the policy constraints in terms of a potential increase in energy security; thus the negative welfare impacts simply convey that there is no free lunch in increasing the share of renewable energy in electricity generation (scenario REN), improving energy efficiency (scenario EFF), or curbing CO_2 emissions (scenario CO2).[20]

Without further qualification, the differences in economic adjustment cost across the three policy scenarios are purely descriptive since we do not measure cost differences across a common metric such as the change in energy security. We come back to this issue in section 4.2.3 where we compare the policies in terms of a cost-effectiveness analysis with respect to specific energy security indicators.

4.2.2 Implications of energy security policies for energy security indicators

Figures 2 to 4 depict for each of three energy security policies REN, EFF, and CO2 how the four energy security indicators change over the range of targeted policy levels. The x-axis shows the policies' target levels while the y-axis shows improvements in indicators as percentage values with respect to the base year level. It is apparent from these figures that only energy efficiency policies (EFF) have an unambiguously positive impact across all energy security indicators while CO_2 reduction (CO2) and renewable promotion (REN) policies trigger ambiguous effects.

[20] The welfare results indicate that there are no substantial second-best effects due to pre-existing tax distortions in the dataset that would make additional constraints under scenarios REN, EFF, or CO2 eventually welfare improving (even without accounting for economic benefits of energy security improvements).

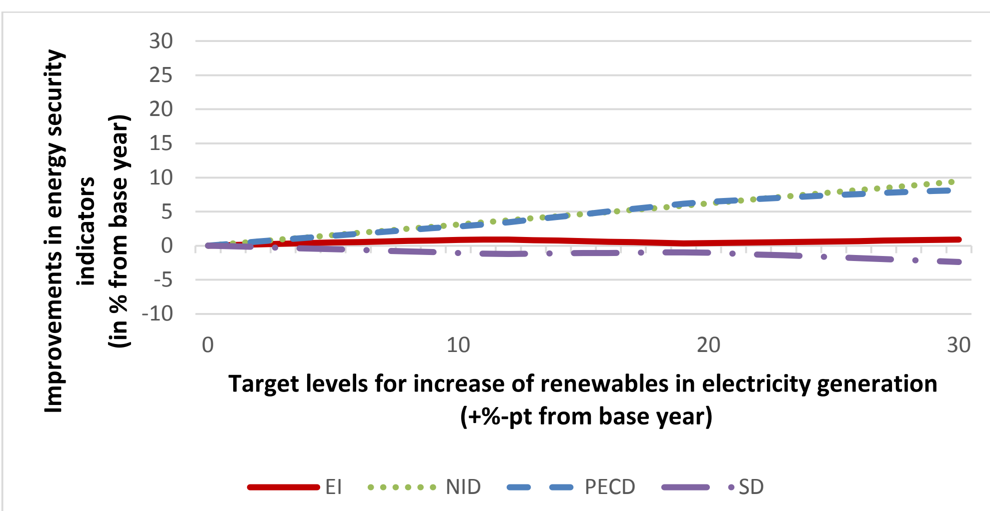
Subsidizing renewables in electricity generation (scenario <u>REN</u> depicted in figure 2) improves net-import dependency (NID) and primary energy carrier dependency (PECD) over the whole range of target levels, while supplier dependency (SD) worsens. This is mainly due to the fact that, while nuclear energy consumption remains at the prescribed base-year upper bound, consumption of renewables increases at the expense of fossil primary energy consumption which in turn implies reduced primary energy imports and more equal supply shares of the different primary energy carriers in total primary energy supply. However, since consumption of coal decreases more than consumption of gas, import shares of gas suppliers increase relative to the import shares of coal suppliers. In the end, this implies a slightly more concentrated supplier mix towards natural gas suppliers. The impact on primary energy intensity of GDP (EI) is negligible.

Taxing primary energy consumption (scenario <u>EFF</u> depicted in figure 3) improves each of the four energy security indicators. Fossil primary energy consumption declines while consumption of nuclear energy again remains at its upper base-year bound and consumption of renewables slightly increases. The reduction in primary energy consumption directly goes along with reduced imports of fossil primary energy. Furthermore, since there is no strong substitution between the different fossil primary energy carriers (in particular between coal and natural gas), primary energy carrier dependency (PECD) and supplier dependency (SD) increase only slightly.

CO_2 emission pricing (scenario CO_2 depicted in figure 4) leads to a decline in primary energy intensity of GDP (EI) as well as the net-import dependency (NID). The improvement in both indicators is linked to the decline in total fossil primary energy consumption. On the contrary, the indicators on primary energy carrier dependency (PECD) and supplier dependency (SD) deteriorate as the diversity of the primary energy mix and diversity of external fossil primary energy suppliers decrease. This is mainly caused by the following three effects. First, carbon taxes decrease consumption of fossil primary energy, while consumption of nuclear energy remains at the upper base-year bound and consumption of renewables increases. The decrease in fossil primary energy consumption thereby offsets the increase in the consumption of renewables. Second, due to differences in carbon intensities, carbon taxes induce substitution of coal for gas. Third, since gas suppliers in general do not supply coal and are fewer in number (see Table 2), substitution of coal for gas results in supplier switching which implies higher import shares of gas suppliers in total primary energy imports. All in all, more stringent CO_2 reduction targets imply that (i) less primary energy is consumed, (ii) less fossil primary energy imports are required, (iii), the primary energy mix becomes more concentrated towards nuclear energy, renewables and natural gas, and (iv) the supplier mix becomes more concentrated towards natural gas suppliers.

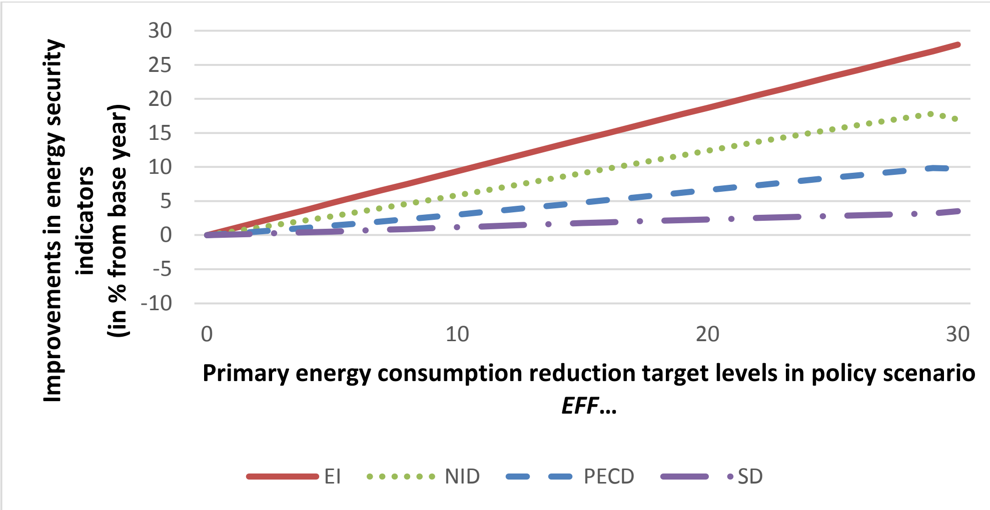
The ambiguity of energy security policies with respect to qualitative effects on energy security indicators reveals the fundamental tension inherent to the broader energy security debate. The heterogeneity in energy security indicators may lead to contradicting conclusions on the desirability of policy measures intended for improvements in energy security. One could argue that different indicators just measure different dimensions of energy security and thus reverse effects in indicators just point to trade-offs across these dimensions. However, for rational decision making such trade-offs must then be clarified through monetarization rooted in rigorous welfare analysis.

Figure 2: Impacts of renewable promotion policies (REN) on energy security indicators



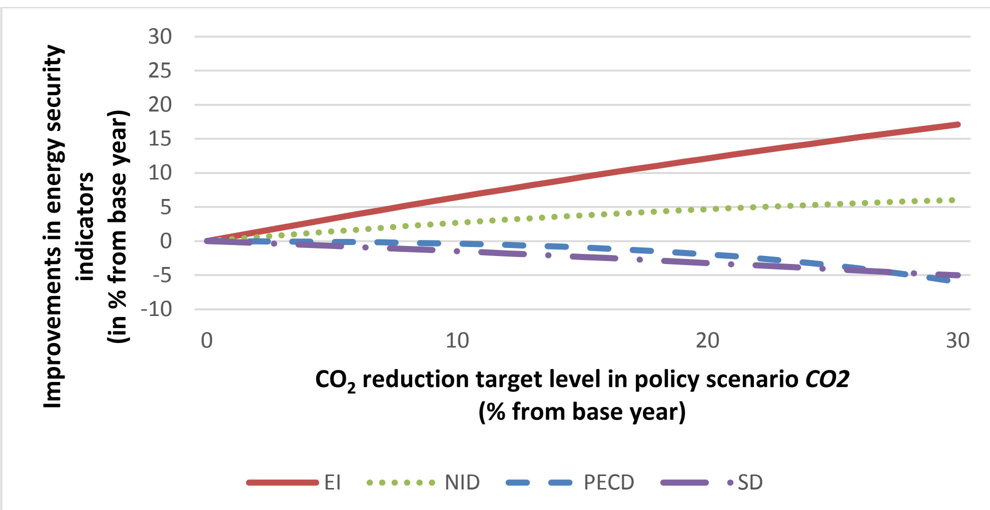
Key: EI – energy intensity of GDP; NID – net-import dependency; PECD – primary energy carrier dependency; SD – supplier dependency

Figure 3: Impacts of energy efficiency policies (EFF) on energy security indicators



Key: EI – energy intensity of GDP; NID – net import dependency; PECD – primary energy carrier dependency; SD – supplier dependency

Figure 4: Impacts of CO_2 reduction policies (CO2) on energy security indicators



Key: EI – energy intensity of GDP; NID – net import dependency; PECD – primary energy carrier dependency; SD – supplier dependency

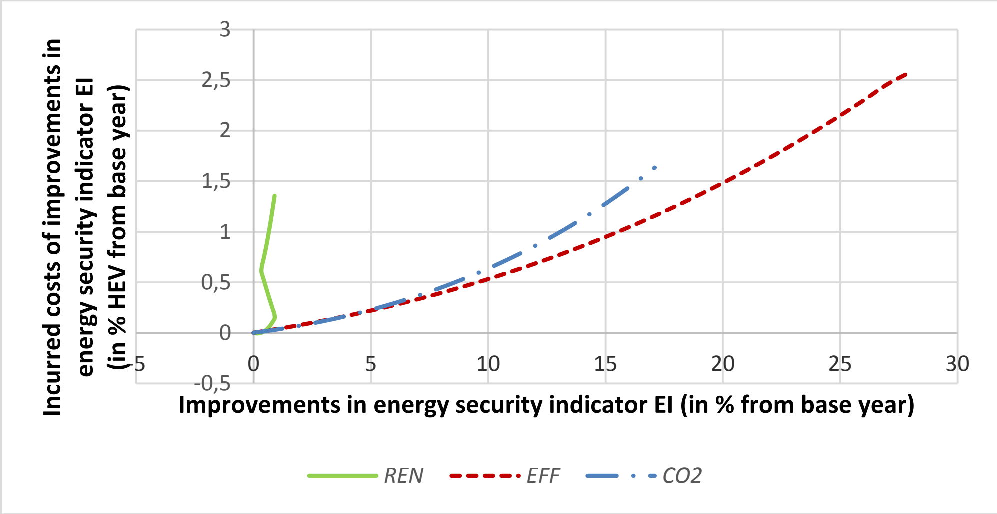
4.2.3 Cost-effectiveness of energy security policies

To qualify the welfare impacts across alternative energy security policies within the limits of our analytical framework one can at least undertake a comparison in their cost-effectiveness with respect to specific energy security indicators. Figure 5 to 8 report the economic adjustment cost across the three policies REN, EFF, and CO2 for changes in indicators: primary energy intensity of GDP (figure 5), net-import dependency (figure 6), fuel mix diversity (figure 7), and supplier mix diversity (figure 8). While the x-axis shows improvements in the indicator value with reference to the base year, the y-axis indicates the associated cost (i.e. welfare losses relative to the base-year welfare measured as HEV).

Obviously, there is no single least-cost policy option with respect to overall energy security, measured in terms of all four energy security indicators. It is possible to identify dominant least-cost policy options for three energy security indicators: promotion of renewables (REN) induces the least cost for improving primary energy carrier dependency (PECD) while increasing energy efficiency (EFF) turns out to be least cost for improving both supplier dependency (SD) as well as total primary energy intensity of GDP (EI). For net-import dependency (NID), there is no dominant strategy since the least-cost option shifts from promotion of renewables to increasing energy efficiency. Interestingly, in four cases we do not get a one to one mapping from the x-axis to the y-axis, i.e. indicator improvements are achieved at various costs. These are energy intensity (EI) and supplier dependency (SD) for promotion of renewables (REN) and net-import dependency (NID) and primary energy carrier dependency (PECD) for increasing energy efficiency (EFF). This is because while economic adjustment costs increase in the target level of each policy, the policies' qualitative impact on energy security indicators is not stable for the identified cases presented above (see corresponding figures in section 4.2.2).

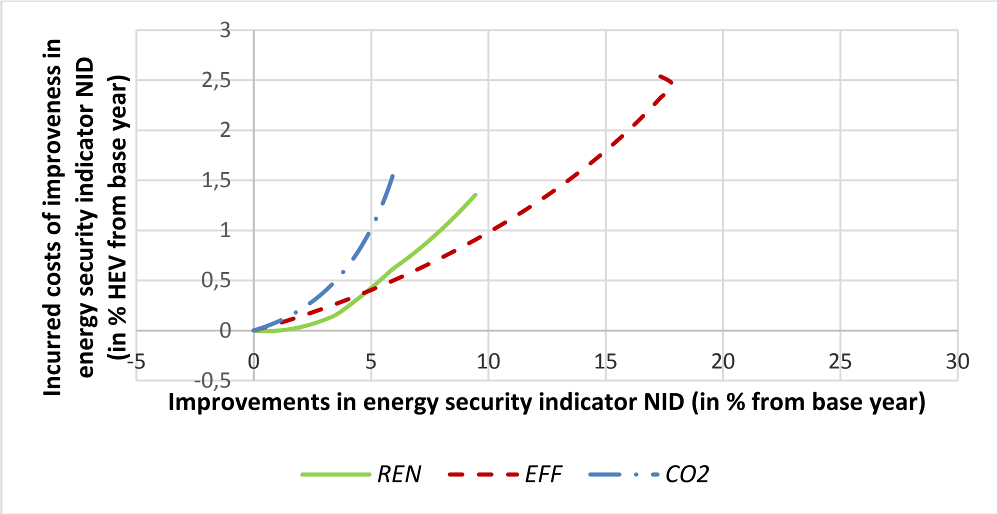
The lack of a single dominant policy strategy for all energy security indicators highlights again the pitfall of using different indicators without having a monetary metric for conversion. Decision makers do not obtain a clear-cut cost-effectiveness ranking of policy options with respect to energy security nor are they in general able to compare changes across different indicators on economic grounds.

Figure 5: Cost-effectiveness of energy security policies w.r.t. energy intensity (EI)



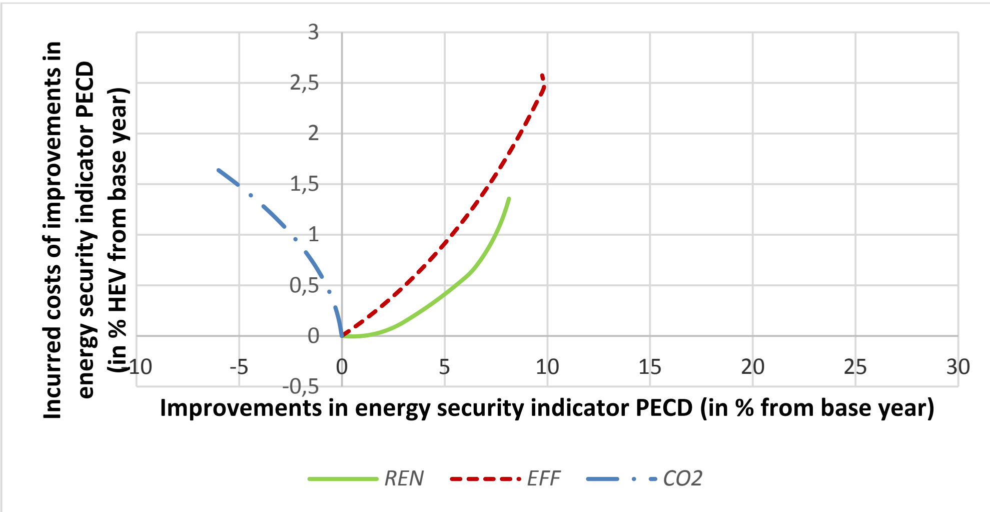
Key: REN – subsidies to renewables in electricity generation for the promotion of renewables; EFF - taxes on primary energy use for improvements in energy efficiency; CO2 - carbon taxes for reducing CO_2 emissions

Figure 6: Cost-effectiveness of energy security policies w.r.t. net-import dependency (NID)



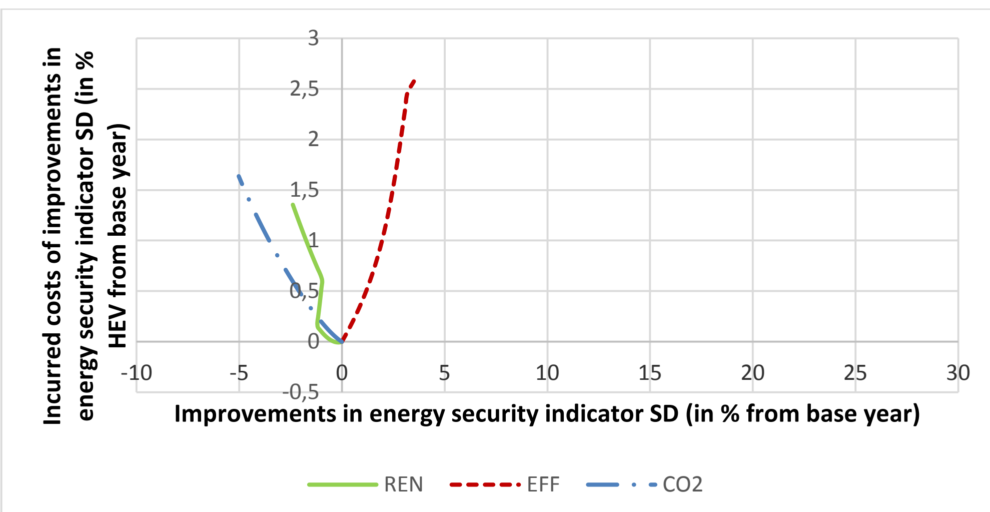
Key: REN – subsidies to renewables in electricity generation for the promotion of renewables; EFF - taxes on primary energy use for improvements in energy efficiency; CO2 - carbon taxes for reducing CO_2 emissions

Figure 7: Cost-effectiveness of energy security policies w.r.t. primary energy carrier dependency (PECD)



Key: REN – subsidies to renewables in electricity generation for the promotion of renewables; EFF - taxes on primary energy use for improvements in energy efficiency; CO2 - carbon taxes for reducing CO_2 emissions

Figure 8: Cost-effectiveness of energy security policies w.r.t. supplier dependency (SD)



Key: REN – subsidies to renewables in electricity generation for the promotion of renewables; EFF - taxes on primary energy use for improvements in energy efficiency; CO2 - carbon taxes for reducing CO_2 emissions

5 Conclusions

Energy security ranks high on the policy agenda of many countries. To improve energy security governments undertake a plethora of measures including the promotion of renewable energy, improvements in energy efficiency, or reductions of CO_2 emissions from fossil fuel combustion. As a metric for energy security, various indicators are commonly used such as the energy intensity of GDP, the (net) import share of energy consumption, the fuel mix diversity, or the diversity of external primary energy suppliers.

In this paper we have used a CGE model of the global economy to highlight fundamental pitfalls of the energy security debate based on a selection of wide-spread energy security indicators and principal energy security policy measures.

Our numerical simulations illustrate that heterogeneity of indicators can lead to conflicting conclusions on the desirability of energy security policies. Regulatory measures such as subsidies for renewable energy or taxes on CO_2 emissions might improve energy security based on one indicator but worsen energy security based on another indicator. Since we cannot aggregate value changes across different indicators, the net effect on energy security remains unclear. Only if all energy security indicators improve due to policy interference one could claim an increase in energy security – in this vein, improving efficiency improvements turns out as the only robust strategy, at least according to the four energy indicators used in our study. Furthermore, it is not possible to derive an unambiguous cost-effectiveness ranking of policy measures across different indicators. As a consequence, policy makers are not able to put decisions on an informed basis rather than on fuzzy or contradicting hunches.

The use of energy security indicators can make sense to provide important insights into specific characteristics and complementary dimensions of energy dependency. For example, they can indicate how major events such as military conflicts, embargoes, or the implementation of transformational energy system policies, change vulnerabilities and affect trade-offs as well as commonalities between different dimensions of energy security (Sovacool, 2013). However, they make no sense as a substitute for rigorous economic cost-benefit analysis of policies addressing energy security. Without a microeconomic foundation, energy security indicators remain descriptive in nature and can't provide guidance into the desirability of energy market interference from a normative perspective. The lack of a money-metric conversion makes it impossible to compare heterogeneous indicators; it is by no means clear how changes in energy security indicators should be valued by the society: An issue which can't be measured in a concise manner is difficult to improve

Adhering to the efficiency paradigm of competitive markets, the economist's contribution to the energy security debate should be the identification of market failures which could justify regulatory intervention. In this vein, the seminal work by Bohi and Toman (1996) provides an overview on potential externalities related to energy security ranging from market power by energy exporting countries via insufficient hedging by private actors to macroeconomic adjustment costs in the case of energy price increases. More recent work by Markandya and Pemberton (2010), Abada and Massol (2011) as well as Eichner and Pethig (2013) elaborate on aspects of risk and uncertainty in energy markets to make the case for insufficient private risk hedging. However, compared with the bulk of literature on energy security indicators, there is a severe lack on economic research to assess the scope and magnitude of externalities with appropriate measures. Without rigorous microeconomic foundation, the notion of energy security remains a vague catchword rather than an operational concept.

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Appendix A: Algebraic model summary

The computable general equilibrium model is implemented as a system of nonlinear inequalities. The inequalities correspond to the two classes of conditions associated with a general equilibrium: (1) zero profit conditions for constant-returns-to-scale producers, and (2) market clearance conditions for all goods and factors. The former class determines activity levels and the latter determines price levels. In equilibrium, each of these variables is linked to one inequality condition: an activity level to a zero profit condition and a commodity price to a market clearance condition. In our algebraic exposition, the index g comprises all sectors/commodities i as well as the composite final consumption good C, the aggregate public consumption good G, and the composite investment good I. The subset of energy goods (coal, refined oil, gas, electricity) is represented by the index EG. The label FF denotes the subset of fossil fuels (coal, crude oil, gas). Regions are indexed with r and aliased with s. Table A.1 provides an overview of the indices and sets used in the algebraic model formulation.

Π_{ir}^{z} represents the unit-profit function for constant-returns-to-scale production in sector i in region r for production activity z. Differentiation of zero-profit conditions based on Hotelling's Lemma results in compensated demand and supply coefficients appearing in the market clearance conditions.

Tables A.2 – A.6 list variables (activity levels and prices) and parameters (cost shares, elasticities of substitution and endowments) of the model. The model is implemented in GAMS and solved using PATH.

Table A.1: Indices and sets

	Indices and sets
g	Index covering all sectors and commodities (i), the final consumption composite (*C*), the investment composite (*I*), and the public good composite (*G*)
i	Index for sectors and commodities
r *(alias* s*)*	Index for regions
$EG(i)$	Set of energy goods: coal, refined oil, gas, electricity
$FE(i)$	Set of fossil fuels with carbon emissions: coal, refined oil, gas
$FF(g)$	Set of exhaustible fossil fuels: coal, crude oil, gas
et	Electricity generation technologies: coal, refined oil, gas, nuclear, renewables

Table A.2: Activity variables

Activity variables	
Y_{gr}	Production of commodity g in region r
M_{gr}	Material composite for commodity g in region r
E_{gr}	Energy composite for commodity g in region r
KL_{gr}	Value-added composite for commodity g in region r
A_{igr}	Armington aggregate of commodity i for demand categories g in region i
IM_{ir}	Aggregate imports of commodity i in region r
$X_{et,r}$	Electricity supply of technology et in region r

Table A.3: Price variables

Price variables	
p_{gr}	Price of commodity g in region r
p_{gr}^{M}	Price of material composite for commodity g in region r
p_{gr}^{E}	Price of energy composite for commodity g in region r
p_{gr}^{KL}	Price of value-added composite for commodity g in region r
p_{igr}^{A}	Price of Armington aggregate of commodity i for demand categories g in region r
p_{ir}^{IM}	Price of aggregate imports of commodity i in region r
w_r	Price of labor (wage rate) in region r
v_r	Price of capital services (rental rate) in region r
q_{ir}	Rent for fossil fuel resources in region r $(i \in FF)$
$p_r^{CO_2}$	Price of carbon emissions in region r
p_r^{PE}	Price of primary energy use in region r
p_r^{OTH}	Price of other inputs in electricity production in region r
$v_{et,r}^{CAP}$	Price of technology specific capital for electricity generation technology et in region r
s_r^{ren}	Subsidy for renewables in electricity generation

Table A.4: Cost shares

	Cost shares
θ_{gr}^{M}	Cost share of the material composite in production of commodity g in region r
θ_{gr}^{E}	Cost share of the energy composite in the aggregate of energy and value-added of commodity g in region r
θ_{igr}^{MN}	Cost share of the material input i in the material composite of commodity g in region r
θ_{igr}^{EN}	Cost share of energy input i in the energy composite of commodity g in region r
θ_{gr}^{K}	Cost share of capital within the value-added of commodity g in region r
θ_{gr}^{Q}	Cost share of fossil fuel resource in fossil fuel production ($g \in FF$) in region r
θ_{gr}^{K}	Cost share of capital in non-resource inputs to fossil fuel production ($g \in FF$) in region r
θ_{gr}^{L}	Cost share of labor in non-resource inputs to fossil fuel production ($g \in FF$) in region r
θ_{igr}^{FF}	Cost share of good i in non-resource inputs to fossil fuel production ($g \in FF$) in region r
θ_{igr}^{A}	Cost share of domestic input i within the Armington composite of commodity g in region r
θ_{isr}^{M}	Cost share of exports of commodity i from region s in the import composite of commodity i in region r
$\theta_{et,r}^{FUE}$	Cost share of fuel input in electricity generation technology et in region r
$\theta_{et,r}^{FE}$	Cost share of fossil fuel in fuel input in electricity generation technology et in region r
$\theta_{et,r}^{CAP}$	Cost share of technology specific capital in non-fuel input in electricity generation technology et in region r

Table A.5: Elasticities of substitution

	Elasticities of substitution
σ_{gr}^{KLEM}	Substitution between the material composite and the energy-value-added aggregate in production of commodity g in region r
σ_{gr}^{KLE}	Substitution between energy and the value-added nest in production of commodity g in region r
σ_{gr}^{M}	Substitution between material inputs within the material composite in production of commodity g in region r
σ_{gr}^{KL}	Substitution between the capital and labor within the value-added composite in production of commodity g in region r
σ_{gr}^{E}	Substitution between energy inputs within the energy composite in production of commodity g in region r
σ_{gr}^{Q}	Substitution between natural resource input and the composite of other inputs in fossil fuel production $(g \in FF)$ in region r
σ_{ir}^{A}	Substitution between import composite and domestic input to Armington production of commodity i in region r
σ_{ir}^{IM}	Substitution between imports from different regions within the import composite for good i in region r
$\sigma_{et,r}^{ET}$	Substitution between technology specific capital and other inputs in electricity generation for electricity generation technology et in region r

Table A.6: Endowments

	Endowments
$\overline{L_r}$	Aggregate labor endowment in region r
$\overline{K_r}$	Capital endowment in region r
$\overline{Q_{ir}}$	Resource endowment of fossil fuel resource i for region r $(i \in FF)$
$\overline{B_r}$	Initial balance of payment deficit or surplus in region r $\left(\sum_r \overline{B_r} = 0\right)$
$\overline{I_r}$	Exogenously fixed investment in region r
$\overline{G_r}$	Exogenously fixed government consumption in region r
$\overline{CO_{2r}}$	Endowment of carbon emission rights in region r
$\overline{PE_r}$	Endowment primary energy consumption rights in region r
$\overline{REN_r}$	Quota on renewables in electricity generation in region r
$a_{igr}^{CO_2}$	Carbon emissions coefficient for fossil fuel i in demand category g of region r $(i \in FF)$
b_{igr}^{PE}	Energy demand coefficient for fossil fuel i in demand category g of region r $(i \in FF)$
$c_{et,r}^{CO_2}$	Carbon emissions coefficient for electricity generation technology et of region r $(i \in FF)$
$d_{et,r}^{PE}$	Energy demand coefficient for electricity generation technology et of region r $(i \in FF)$

Zero profit conditions

- Production of goods except fossil fuels ($g \notin FF$)

$$\Pi_{gr}^{y} = p_{gr} - \left[\theta_{gr}^{M} {p_{gr}^{M}}^{(1-\sigma_{gr}^{KLEM})} + \left(1-\theta_{gr}^{M}\right)\left[\theta_{gr}^{E} {p_{gr}^{E}}^{(1-\sigma_{gr}^{KLE})} + \left(1-\theta_{gr}^{E}\right) {p_{gr}^{KL}}^{(1-\sigma_{gr}^{KLE})}\right]^{\frac{(1-\sigma_{gr}^{KLEM})}{(1-\sigma_{gr}^{KLE})}}\right]^{\frac{1}{(1-\sigma_{gr}^{KLEM})}} \leq 0 \qquad (\text{A.1})$$

- Sector-specific material input

$$\Pi_{gr}^{M} = p_{gr}^{M} - \left[\sum_{i \notin EG} \theta_{igr}^{MN} \left(p_{igr}^{A} + p_{r}^{PE} b_{igr}^{PE}\right)^{(1-\sigma_{gr}^{M})}\right]^{\frac{1}{(1-\sigma_{gr}^{M})}} \leq 0 \qquad (\text{A.2})$$

- Sector-specific energy aggregate

$$\Pi_{gr}^{E} = p_{gr}^{E} - \left[\sum_{i \in EG} \theta_{igr}^{EN} \left(p_{igr}^{A} + p_{r}^{CO_2} a_{igr}^{CO_2} + p_{r}^{PE} b_{igr}^{PE}\right)^{(1-\sigma_{gr}^{E})}\right]^{\frac{1}{(1-\sigma_{gr}^{E})}} \leq 0 \qquad (\text{A.3})$$

- Sector-specific value-added aggregate

$$\Pi_{gr}^{KL} = p_{gr}^{KL} - \left[\theta_{gr}^{K} {v_{r}}^{(1-\sigma_{gr}^{KL})} + \left(1-\theta_{gr}^{K}\right) {w_{r}}^{(1-\sigma_{gr}^{KL})}\right]^{\frac{1}{(1-\sigma_{gr}^{KL})}} \leq 0 \qquad (\text{A.4})$$

- Production of fossil fuels ($g \in FF$)

$$\Pi_{gr}^{Y} = p_{gr} - \left[\theta_{gr}^{Q} q_{gr}{}^{\left(1-\sigma_{gr}^{Q}\right)} + \left(1 - \theta_{gr}^{Q}\right) \left[\theta_{gr}^{L} w_r + \theta_{gr}^{K} v_r + \sum_i \theta_{igr}^{FF} \left(p_{igr}^{A} + p_r^{CO_2} a_{igr}^{CO_2} + p_r^{PE} b_{igr}^{PE} \right) \right]^{\left(1-\sigma_{gr}^{Q}\right)} \right]^{\frac{1}{\left(1-\sigma_{gr}^{Q}\right)}} \leq 0 \qquad \text{(A.5)}$$

- Armington aggregate

$$\Pi_{igr}^{A} = p_{igr}^{A} - \left[\theta_{igr}^{A} p_{ir}{}^{\left(1-\sigma_{ir}^{A}\right)} + \left(1 - \theta_{igr}^{A}\right) p_{ir}^{IM}{}^{\left(1-\sigma_{ir}^{A}\right)} \right]^{\frac{1}{\left(1-\sigma_{ir}^{A}\right)}} \leq 0 \qquad \text{(A.6)}$$

- Aggregate imports across import regions

$$\Pi_{ir}^{IM} = p_{ir}^{IM} - \left[\sum_s \theta_{isr}^{IM} \, p_{is}^{\left(1-\sigma_{ir}^{IM}\right)} \right]^{\frac{1}{\left(1-\sigma_{ir}^{IM}\right)}} \leq 0 \qquad \text{(A.7)}$$

- Technology-specific (bottom-up) electricity generation

$$\Pi_{et,r}^{X} = p_{ELE,r} - \left[\theta_{et,r}^{FUE} \sum_{i \in FE} \theta_{et,r}^{FE} p_{i,ELE,r}^{A} + \left(1 - \theta_{et,r}^{FUE}\right) \left[\theta_{et,r}^{CAP} v_{et,r}^{CAP}{}^{\left(1-\sigma_{et,r}^{ET}\right)} + \left(1 - \theta_{et,r}^{CAP}\right) p_r^{OTH}{}^{\left(1-\sigma_{et,r}^{ET}\right)} \right]^{\frac{1}{\left(1-\sigma_{et,r}^{ET}\right)}} + p_r^{CO_2} c_{et,r}^{CO_2} + p_r^{PE} d_{et,r}^{PE} - s_r^{ren} \right] \leq 0 \qquad \text{(A.8)}$$

Market clearance conditions

- Labor

$$\overline{L_r} \geq \sum_g Y_{gr}^{KL} \frac{\partial \Pi_{gr}^{KL}}{\partial w_r} \tag{A.9}$$

- Capital

$$\overline{K_{gr}} \geq Y_{gr}^{KL} \frac{\partial \Pi_{gr}^{KL}}{\partial v_r} \tag{A.10}$$

- Fossil fuel resources ($g \in FF$)

$$\overline{Q_{gr}} \geq Y_{gr}^{KL} \frac{\partial \Pi_{gr}^{Y}}{\partial q_{gr}} \tag{A.11}$$

- Material composite

$$M_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{M}} \tag{A.12}$$

- Energy composite

$$E_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{E}} \tag{A.13}$$

- Value-added

$$KL_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{KL}} \tag{A.14}$$

- Import composite

$$IM_{ir} \geq \sum_g A_{igr} \frac{\partial \Pi_{igr}^{A}}{\partial p_{ir}^{IM}} \tag{A.15}$$

- Armington aggregate

$$A_{igr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{igr}^{A}} \qquad \text{(A.16)}$$

- Commodities $(g = i)$

$$Y_{ir} \geq \sum_{g} A_{igr} \frac{\partial \Pi_{igr}^{A}}{\partial p_{ir}} + \sum_{s \neq r} IM_{is} \frac{\Pi_{is}^{IM}}{\partial p_{ir}} \qquad \text{(A.17)}$$

- Private consumption $(g = C)$

$$Y_{Cr} p_{Cr} \geq w_r \overline{L_r} \sum_{g} v_{gr} \overline{K_{gr}} + \sum_{i \in FF} q_{ir} \overline{Q_{ir}} + B_r \qquad \text{(A.18)}$$

- Public consumption $(g = G)$

$$Y_{Gr} \geq \overline{G_r} \qquad \text{(A.19)}$$

- Investment $(g = I)$

$$Y_{Ir} \geq \overline{I_r} \qquad \text{(A.20)}$$

- Carbon emissions:

$$\overline{CO_{2r}} \geq \sum_{g} \sum_{i \in FE} A_{igr} a_{igr}^{CO_2} \qquad \text{(A.21)}$$

- Primary energy consumption:

$$\overline{PE_r} \geq \sum_{g \notin ELE} \sum_{i \in XE} A_{igr} b_{igr}^{PE} + \sum_{et} X_{et,r} d_{et,r}^{PE} p_r^{PE} \qquad \text{(A.22)}$$

- Quota on renewables in electricity production:

$$\overline{REN_r} \leq X_{ren,r} \qquad (A.23)$$

Appendix B: Nesting of functional forms

Figure B.1: Non-fossil fuel production

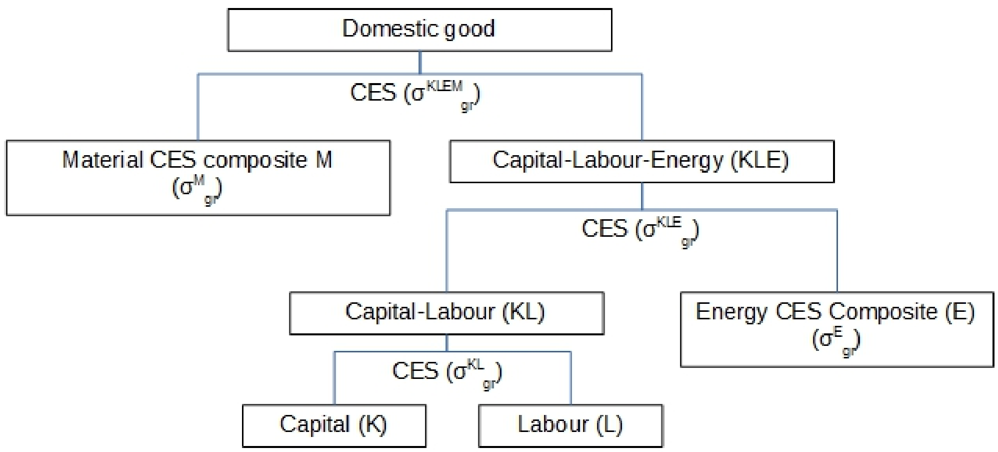


Figure B.2: Fossil fuel production

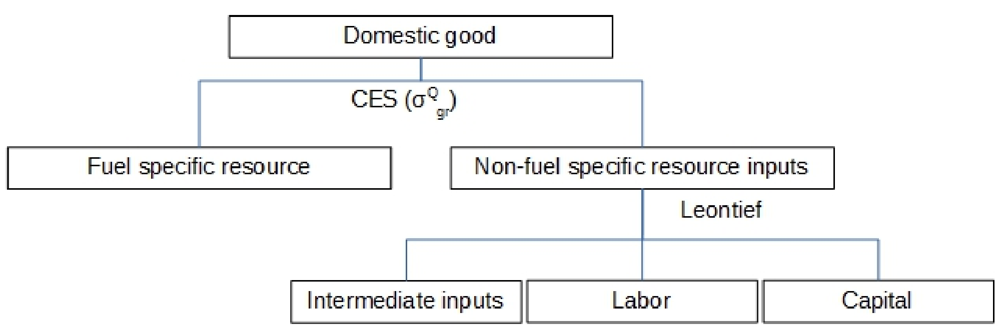


Figure B.3: Armington good

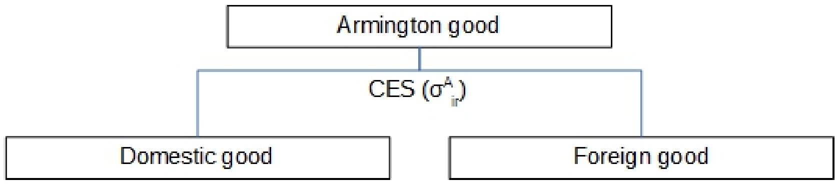
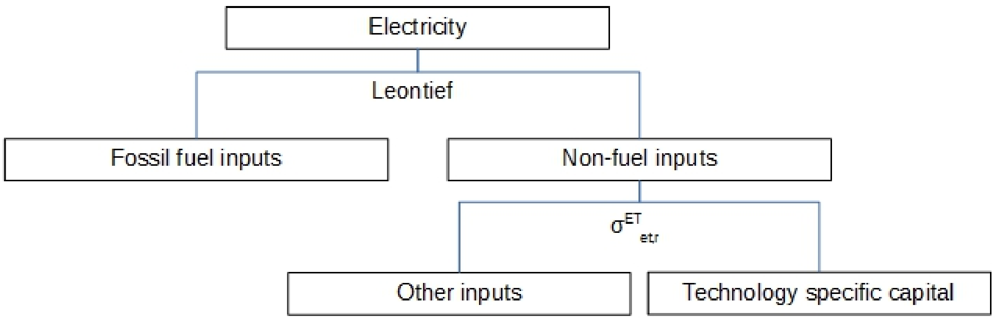


Figure B.4: Technology-specific (bottom-up) electricity generation



Appendix C: Region- and fuel specific risk factors

Table C.1: Region- and fuel-specific risk factors

	Coal	Crude oil	Gas
OECD countries and Russia			
EU27	1,18	1,08	1,07
Australia	1,07	1,07	1,07
Canada	1,07	1,07	1,07
Japan	1,13	1,13	1,13
Norway	1,08	1,08	1,08
Russia	1,48	1,48	1,48
USA	1,15	1,15	1,15
Non-OECD countries (excl. Russia)			
Azerbaijan	1,47	1,47	1,47
Brazil	1,40	1,40	1,40
China	1,42	1,42	1,42
Columbia	1,52	1,52	1,52
India	1,51	1,51	1,51
Indonesia	1,52	1,52	1,52
Iran	1,64	1,63	1,64
Kazakhstan	1,33	1,32	1,33
Nigeria	1,67	1,67	1,67
Saudi Arabia	1,40	1,40	1,40
South Africa	1,27	1,27	1,27
Rest of Western Asia	n.a.	1,76	n.a.
Rest of North Africa	1,64	1,49	1,54
Other OECD countries	1,04	1,39	1,39
Other OPEC countries	n.a.	1,40	n.a.
Other non-OPEC countries	1,41	1,41	1,43

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