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DISSERTATION

Three Essays in Energy and Environmental Economics

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Declaration of Authorship

The author hereby declares that he compiled this thesis independently; using only the listed resources and literature, and the thesis has not been used to obtain a different or the same degree.

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Signature

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Abstract

This thesis consists of three articles that share the main theme – energy and environment. The dissertation aims mainly at the Czech energy system and analyses it development after the Velvet Revolution and its possible future development.

The first article applies Logarithmic Mean Divisia Index decomposition to analyses the main driving forces of significant reduction in air quality pollutants during the transition of the Czech economy towards market economy in the 1990s. It continues then to investigate how the driving forces affected the emissions volumes during succeeding the post-transition period up to 2016.

The second article reacts on the 2015 governmental decision to lift brown coal mining limits in the North Bohemia coal basin. The paper analyses the impacts of maintaining the ban on mining coal reserves and compares them with three alternative options that would each weaken the environmental protections of the ban. The impacts of each of these alternative governmental propostions are analysed on the Czech energy system, the fuel- and the technology-mix, the costs of generating energy, related emissions and external costs associated with the emissions.

The third article analyses the impact of massive increase in wind and solar installations in Germany on transmission networks in the Central Europe. The German policy "*Energiewende*" and insufficient transmission capacity between the northern and the southern part of Germany and the German-Austrian bidding zone have all heavily contributed to congestion in the Central European transmission system. The article assesses this impacts on relevant transmission grid. Two scenarios for the year 2025 are evaluated on the basis of four representative weeks.

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Contents

Acronyms

ACER - Agency for the Cooperation of Energy Regulators

BAT - Best available technologies

CDF - Contract for a difference

CE - Central Europe

CEE - Central and Eastern European

CO - carbon monoxide

CO_2 - carbon dioxide

ČEPS – Czech TSO

ELMOD - A Model of the European Electricity Market

ETS - Emission Trading System

EUA - European Emission Allowances

ExternE - Externalities of Energy

GAMS - General Algebraic Modeling System

GHG - greenhouse gas

IDA - index decomposition analysis

IPA - Impact Pathway Analysis

IPAT - impact population affluence technology

IPCC - International Panel on Climate Change

IPPC - Integrated Pollution Prevention and Control

LMDI - logarithmic mean Divisia index

LULUCF - Land Use and Land Use Change and Forestry Use

MESSAGE - Model for Energy Supply Strategy Alternatives and their General Environmental Impact

NACE - nomenclature of economic activities

NO_x - nitrogen oxides

OECD - Organisation for Economic Co-operation and Development

PM - particulate matter

PSE – Polish TSO

RES - renewable energy sources

SEP - State Energy Policy

SO_2 - sulphur dioxide

TEL - Territorial Environmental Limits

TIMES - The Integrated MARKAL-EFOM System

TSO - transmission system operator

UNEP - United Nations Environment Programme

VRES - variable renewable energy sources

WEO - World Economic Outlook

WMO - World Meteorological Organization

1. Introduction

Economic growth and improvements in global living standards have been correlated with increases in energy consumption and growing demand for energy services. This demand is satisfied through joint use of energy-related durables and non-durable energy goods to generate energy services. Non-durable energy goods are typically electricity and heat, which may be generated either by fossil fuel combustion, nuclear energy transformation, or by renewable energy sources. Energy generation generates a wide range of side effects at various stages, including pollution. Emissions of air quality pollutants lead to adverse impacts on the environment and human health (Kampa & Castanas, 2008), and greenhouse gas emissions generated by energy production and consumption induce climate change (Stern, 2007). These negative impacts are not (or not fully) compensated in the market (Coase, 1960) and economic theory denotes them as negative externalities (Baumol & Oates, 1988). To maximise social welfare, economic theory requires market interventions to correct for these Pigouvian externalities (Goulder & Parry, 2008; Pigou, 1920; Sandmo, 1978). This dissertation thesis addresses these points, aiming specifically at markets in which energy is generated, and examining further the economic factors that affect the volumes of emissions stemming from energy generation. One factor we pay special attention to is regulation and the impacts that it can induce in energy systems, including effects on emissions and associated external costs. For this purpose, we develop several modelling tools.

Energy industries and markets have developed from relatively simple local natural monopolies to complex systems and global markets of energy commodities and derivates. However, the network industries – oil, gas, power and heat – have never reached a state of perfect market competition, and so more and more robust regulation has been imposed upon these industries over time (Florio, 2017). In addition to market regulations, in the second half of the 20th century, developed countries began to introduce environmental policies aimed to reduce emissions of air pollutants. These policies have become stricter in their effects and wider in their scope over time. In 1988, the International Panel on Climate Change (IPCC) was established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), and policy has widened its focus to address climate change impacts.

All this has motivated my research focusing on energy and environmental economics, especially in Central Europe and the Czech Republic. Energy systems and industries are very complex; this is certainly true in the Czech Republic. Additionally, the Czech economy and its energy sector underwent the transition from a communist regime and central market planning towards democracy and a market economy in the 1990s (Kouba, Vychodil, & Roberts, 2005).

At the beginning of that time period, environmental quality was poor. For example, the "Black Triangle"[1] region of the Czech Republic was among the most polluted areas in Central Europe (Ürge-Vorsatz, Miladinova, & Paizs, 2006), and the landscape of North Bohemia was devastated by brown coal mining (Glassheim, 2006).

The first democratically elected Czech government began to institute more environmental protections, and in order to comply with the Community Acquis of the EU, several policies to decrease pollution emission levels were introduced. The new Air Quality Act No. 309/1991 and related regulations[2], which required each existing large stationary emission source (power plants and industrial factories) to comply with strict emissions limits until 1998, were the main drivers of a large reduction in emissions of air pollutants in the Czech Republic during the 1900s, particularly those of SO_2, NO_x, and PM. Following this Act, emissions limits were set in 1991 and have since been strengthened several times (1992, 1995, 1997 and 2002), in the form of command-and-control regulation. Newly introduced economic instruments aimed to reduce air pollutants emissions in the 2000s were quite ineffective due to low tax rates (in the case of energy taxes) or because of over-allocation of CO_2 allowances within the first phase of the EU ETS (Ščasný & Máca, 2009). As a consequence, as all large emission sources sources reached their emission limits by 1999, the emission levels of air quality pollutants decreased only slightly over the next decade. Integrated permits introduced under *Integrated Pollution and Prevention Control*[3] (IPPC) and concentration limits on pollutants in flue gas were the only truly effective instruments regulating airborne emissions from large stationary emissions sources in the 2000s. The European directive on industrial emissions, 2010/75/EU, has induced further strengthening of airborne emissions regulations. However, the Czech Republic negotiated a transition period for implementation of this directive to the end of 2016. This means most of the current large emission sources were not required to meet new emission limits prior to the end of 2016.

Since 1990, the European electricity market has seen significant developments. The most significant milestones include decoupling of electric utilities (Brennan, 2010); European

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[1] The “Black triangle” is the area of northern Bohemia, southern Saxony and part of lower Silesia.

[2] Act No. 309/1991 applied at the federal level (Czechoslovakia). Act No. 389/1991 applies at the national level (the Czech Republic). Act No.309 determines the emissions limits and deadlines necessary to fulfil the requirements, while Act No. 389 defines administration of the process and competences for the relevant authority, Česká inspekce životního prostředí (the Czech Environment Inspectorate).

[3] Based on Act no. 76/2002 Coll., on Integrated Prevention, the regional authorities are in charge of issuing the integrated permits to industrial and agricultural installations (the Ministry of the Environment issues permits for installations with transboundary environmental impacts). The integrated permit replaces most of the sectoral permits (such as air and water protection, waste treatment, etc.).

electricity market liberalization and integration (Jamasb & Pollitt, 2005); creation of the European Union Emissions Trading Scheme (EU ETS) (Convery, 2009); rapid development of wind and solar energy sources fostered by public subsidies (Cansino, Pablo-Romero, Román, & Yñiguez, 2010; Ringel, 2006); and the accident at the Fukushima Daiichi Nuclear Power Station in 2011, which accelerated nuclear phase-out in Germany and some other European countries (Wittneben, 2012).

In addition to the impacts of European trends, the Czech energy system is affected by at least three specific issues: Territorial Environmental Limits; nuclear energy policy; and aversion to renewable energy sources due to a negative experience with a support scheme for photovoltaics.

- The Czech government decided to restrict brown coal mining to specified 'Territorial Environmental Limits' (TEL) in the North Bohemia coal basin in 1991.[4]Since then, a number of parties have called for the re-opening of the brown coal pits most affected by the restriction – Bílina and ČSA – on the basis of social concerns (to ensure the delivery of cheap coal for central heating), regional employment and energy security (domestic coal supply). Despite this pressure, the Czech government re-confirmed the ban in 2008. A change came in October 2015, when the Czech government lifted the TEL. The government had taken into consideration four variants of retaining or abandoning the TEL. The government did not decide to retain the brown coal mining limits unchanged (TEL1 variant), but in order to ensure a supply of high quality domestic brown coal, particularly to supply Czech heat generating plants, it revoked its past binding decision and voted in favour of lifting the brown coal mining limits at the Bílina open pit (TEL2). Two additional options concerning the TEL – partial lifting of the restrictions (TEL3) or even completely abandoning the mining limits on the second open pit (ČSA) (TEL4) – remain still in the game, as the Czech government has stated that lifting mining limits at the ČSA pit might be re-considered as part of the next revision(s) of the Czech State Energy Policy (SEP).
- In 2000 and 2002, the first and second reactors of the Temelín nuclear power plant were commissioned. Since then, the Czech Republic has become one of the largest electricity exporters in the EU. The older Dukovany nuclear power plant consists of four reactors, which are permitted to operate until 2025. Extension of operations up to 2035 should be technologically possible and is assumed by SEP (MPO, 2015), but may not be politically acceptable due to political pressure from the EU (particularly Austria), calling for the shut-down of the Dukovany power plant before 2027. The Czech State Energy Policy

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[4] The limits define the areas where open-pit mining is allowed and where it is not, and are legally binding according to Decrees No. 331 and 444 on Territorial Environmental Limits on Mining passed in 1991, and further re-confirmed by Decree 1176/2008, by the Government of the Czech Republic.

adopted in 2015 anticipates one nuclear new reactor at the existing Dukovany nuclear site and possibly three more at Dukovany and Temelín might be built around 2035, although utility ČEZ cancelled a public tender on building two new nuclear reactors was in 2014 due to the unwillingness of the government to provide price guarantee through contract for difference. Currently, construction financing for any new nuclear reactor is still undecided and the government has already postponed the decision several times (ČTK, 2019). That means the question of a new nuclear power plant and thus also the future of the Czech power system remain open.

- Many large photovoltaic power plants (PV) were built in the period 2008 – 2010, because the PV were overcompensated for financially. In 2008, the Czech government guaranteed PV feed-in tariffs for 20 years, at a rate 95 % higher than in Germany (Ayompe & Duffy, 2013). This made photovoltaics a riskless investment. In 2008, the total installation of PV in the Czech Republic was only 40 MW, but rapidly grew to 1820 MW connected to the grid at the end of 2010. The issue was that, even though the cost of PVs was brought down by cheap technology in 2009 – 2010 (Feldman et al., 2012), the feed-in tariffs were not adjusted accordingly. The subsidies for PV are reflected in surcharges for renewable sources paid by consumers, and have rapidly increased due to this overcompensation and high rates of PV installations. The surcharge for renewable sources paid by consumers amounted to 166.34 CZK/MWh (approximately 6.7 EUR/MWh) in 2010 and jumped 419.22 CZK/MWh (16.8 EUR/MWh) in 2012, an increase of 152% (Průša, Klimešová, & Janda, 2013, p. 747). Although the Czech government reduced the feed-in tariffs retroactively, this experience has damaged public support for all renewable energy sources.

To understand the Czech energy system and, in particular, how national and EU-wide policies may affect this system and consequently the production of emissions, we focus first on *ex post* analysis. **Chapter 2** analyses the main driving forces of significant reductions in air quality pollutants during the transition of the Czech economy towards a market economy in the 1990s and how these driving forces affected emissions volumes across the post-transition period to 2007. We then continue to investigate how the driving forces affected emissions volumes during the succeeding the post-transition period up to 2016. We use Logarithmic Mean Divisia Index decomposition (Ang & Liu, 2001) and statistically decompose annual changes in the emissions levels from large stationary emission sources of four types of air quality pollutants, SO_2, NOx, CO and particulate matters over the period 1990–2016. While most previous decomposition studies have been decomposing emissions into scale, structure and emission intensity factors, a unique environmental dataset allows us to further decompose the emission per output effect into [i] the emission-fuel factor, [ii] the fuel-mix factor, and [iii] the fuel-intensity factor, yielding a 5-factor decomposition. This paper follows up a couple of studies conducted in the

Czech Republic that have not been published in scientific journals: Brůha & Ščasný (2006) apply the Laspeyres method for a 3-factor decomposition analysis on air pollutant emissions in the Czech Republic for the period 1992-2003. A shortcoming of this method is that it generates the residuals. Ščasný & Tsuchimoto (2013) and Tsuchimoto & Ščasný (2012) overcome the problem with the residuals and conduct 3-, 4-, and 5-factor LMDI decomposition analyses of air pollutant emissions for the period of 1995-2007. The added value of this paper is that we use extended and more detailed datasets. We extend the time span to 1990-2016, paying special attention to consistent classification of firms into economic sectors, and we use eight categories of fuel instead of five. As a result, we are able to identify the significant role of the fuel intensity effect in 1990-1992 and to capture the fuel mix effect for CO emissions from 2008 to 2016.

The largest drop in emissions of all four pollutants occurred from 1990 to 1999, when the emissions decreased cumulatively by at least 74 % (CENIA, 2005). In this period, Czech firms faced a newly-competitive environment and new command-and-control regulations and the resulting negative emission-fuel intensity effect was the key driver of emissions reductions. However, the fuel intensity effect contributed most to reduction of SO_2, NOx and PM emissions in the first 3 years after 1989. Since 2008, activity, structure, fuel-intensity and emission-fuel factors have contributed to emissions decreases by similar magnitudes, but mainly activity and fuel-intensity in positive directions. In 2015 and 2016, the emission-fuel effect again became important, as the large stationary emission sources had to comply with new strict emission limits based on the directive on industrial emissions.

Our research conducted in the third part of this dissertation thesis aims at *ex ante* analysis of the Czech energy system and assesses the impacts of national and EU-wide policies on this system. This study follows our earlier research in which we built an optimization model of the Czech electricity system based on the MESSAGE model (Rečka & Ščasný, 2013). Later, our modelling effort moved to a more robust energy system model, TIMES (*The Integrated MARKAL-EFOM System*), to describe the energy system in more detail and with more precision. Its first version mainly focused on the power sector. Using this model, Rečka & Ščasný (2016) analysed the potential impacts of carbon pricing, brown coal availability and price of natural gas on Czech heat and power systems up to 2050. The next step was to extend this model to represent the overall energy balance of the Czech Republic. This extension has been built in the TIMES model version 2.

Chapter 3 "Impacts of Reclassified Brown Coal Reserves on the Energy System and Deep Decarbonisation Target in the Czech Republic" was published in *Energies* 10(12), in 2017. This analysis is based on the most recent version of the TIMES model. The paper itself is a reaction to the 2015 governmental decision to lift brown coal mining limits in the North Bohemia coal basin (*"Prolomení limitů těžby"*). The paper analyses the impacts of maintaining the ban on mining coal reserves and compares them with three alternative options that would each weaken the environmental protections of the ban. The impacts of each alternative proposition are analysed on the Czech energy system, the fuel- and the technology-mix, the costs of generating energy, related emissions and external costs associated with the emissions. The technology scenario and modelling impacts cover the period up to 2050. We find that, overall, the effect of lifting the ban on coal usage, air pollutant emissions and hence externalities would be rather small, up to 1–2% compared to the levels projected if the ban is maintained. The environmental and external health costs attributable to emissions of local air pollutants stemming from power generation are in the range of €26–32 billion over the whole period and decline from about 0.5% of the gross domestic product in 2015 to 0.1% in 2050. The impacts of the three proposed policy options do not differ much from the impacts of the pre-2015 policy plan, which would maintain the ban up to 2050. The differences in the impacts remain small even for various assumption sets. The predictions hold for various assumptions on prices of fossil fuels, costs of the European Emission Allowances to emit carbon emissions, and developments in nuclear power technology deployment. In fact, changing the assumptions on the model inputs (prices, EUA costs, and technology deployment) result in larger differences in the impacts than the differences driven by the four policy options. Even maintaining the ban – the most stringent policy scenario – would not lead to achievement of the European Energy Roadmap 2050 targets. The newly adopted lifting of brown coal mining limits, as well as the other two counter-environmental proposals, would all fail to achieve the 80% carbon emission reduction target to an even greater degree. Research using the TIMES model is further published in another article (Rečka & Ščasný, 2018).

The fourth part of the thesis addresses the technical details of electricity system and expands its geographical focus to Central Europe (CE). This research is summarized in **Chapter 4** "Influence of renewable energy sources on transmission networks in Central Europe", published in *Energy Policy* 108 (2017). This study reacts to recent and expected developments in power and transmission systems in Central Europe. A combination of increases in intermittent sources, especially wind installations not backed by sufficient transmission infrastructure development in Germany, and a single market zone comprised of Germany and Austria, enabling unlimited market transactions between these countries, has resulted in physical power flows that bypass Germany through Polish and Czech transmission networks –

so called loop flows[5] (Boldiš, 2013). Czech, Hungarian, Polish and Slovak transmission system operators (TSOs) have responded to this by insisting that the German-Austrian bidding zone should be broken up (ČEPS, MAVIR, PSE, & SEPS, 2012), a move which was also supported by the Agency for the Cooperation of Energy Regulators (ACER) (ACER, 2015), or even suggesting that Germany should be divided into several zones. The TSOs have also attempted to solve this problem by installing phase-shifting transformers that should be able to halt physical electricity flows in case of emergency. Although the Czech, Hungarian, Polish and Slovak TSOs support their position through a study of unplanned flows in Central and Eastern Europe (ČEPS, MAVIR, PSE, & SEPS, 2013), the Director of Directorate-General Energy declared in January 2016 that the European Commission is against breaking up the bidding zone as it considers this step to be "meaningless" (Kamparth, 2016)[6]. The impacts of introducing smaller bidding zones are also assessed by Egerer, Weibezahn, & Hermann, (2016) and Trepper, Bucksteeg, & Weber, (2014). Glachant & Pignon, (2005) point out TSOs set directly congestion signals in charge of the security of the system and analyse two congestion management methods in Nordic countries.

The majority of the literature assesses the influence of renewables on transmission networks only in the context of Germany (e.g. Kunz, 2013; Kunz & Zerrahn, 2015; A. Singh, Willi, Chokani, & Abhari, 2014; Winkler, Gaio, Pfluger, & Ragwitz, 2016) or on the pan-European level (e.g. Boie, Fernandes, Frías, & Klobasa, 2014; Schaber, Steinke, & Hamacher, 2012; Schaber, Steinke, Mühlich, & Hamacher, 2012)). The literature on transmission networks and the grid in CE is significantly less extensive. Apart from the above-mentioned "German" papers and studies focusing on the bidding zones, there are a few other articles which deal mostly with optimal grid extension or the integration of renewables into the grids. The grid-related literature in Poland has most frequently examined the possibilities of phase-shifting transformers (Korab & Owczarek 2016; Kocot et al. 2013).

The literature assessing the influence of renewables on transmission networks with a focus on the overall CE region is very sparse. A few examples include recent articles by Antriksh Singh, Frei, Chokani, & Abhari, (2016), analysing the impact of unplanned power flows on transmission networks in Austria, Czechia, Germany and Poland, Eser, Singh, Chokani, & Abhari, (2015), who assess the impact of increased renewable penetration under network development, and Kunz & Zerrahn (2016), focusing on cross-border congestion management.

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[5] „Electricity current takes the path of least resistance. When power is produced in one place to supply a consumer elsewhere, it should mainly flow along the most direct power lines between the two. But if the route is congested it will take a detour through other parts of the grid – looping around the blockage. This can result in the current ending up in unexpected places and even flowing through the grids of neighbouring countries."(Russel & Schlandt, 2015, p. 1)

[6] The European Commission reconsidered its opinion later and the common power price zone between Austria and Germany has been splitted since 1 October 2018. We conducted our research before this decision was made and we were unable to respond to it in our analysis.

We aim to fill this gap by analysing the impact of massive increases in wind and solar installations in Germany on transmission networks in Central Europe.
To assess this impact on relevant transmission grids, we built and employed a direct current load flow model, ELMOD. We then evaluated two development scenarios for 2025 on the basis of four representative weeks. The first scenario focuses on the effect of "*Energiewende*" on the transmission networks and the second drops nuclear phase-out and thus assesses the isolated effect of increased feed-ins of renewable energy.

Our results indicate that higher feed-ins of solar and wind power increase the exchange balance and total transport of electricity between transmission system operator areas and the average load of lines and volatility of flows. Solar power is identified as a key contributor to the volatility increase, while wind power is identified as a key loop-flow contributor. Ultimately, the work concludes that German nuclear phase-out does not significantly exacerbate volatility or loop-flows. To our knowledge, no other study on the loop-flows in Central Europe has been published. Research focused on other aspects of *Energiewende* based on the ELMOD model was published in Janda, Málek, & Rečka (2017) and Málek, Rečka, & Janda (2017).

The objective of this dissertation is to contribute to the understanding of the energy and environmental problems related to the Czech energy system by means of three assessment models developed in the research of this thesis. In particular, it identifies the drivers of air pollutant emissions reductions from large stationary emission sources since 1990; it assesses the impact of lifting brown coal mining limits in North Bohemia on the Czech energy system; and finally, it analyses the impacts of increases in renewable energy source generation in Germany on transmission grids in Central Europe. The research results presented also extend existing knowledge of the various driving forces acting in energy systems. The work enriches energy economics and provides valuable inputs for evidence-based policy.

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2. LMDI Decomposition of Air Pollutants in the Czech Republic between 1990 and 2016

Abstract: We examine the main driving forces of significant reductions in air pollutants that occurred during the transition of the Czech economy towards a market economy in the 1990s and how these driving forces affected emissions volumes across the post-transition period to 2016. Using Logarithmic Mean Divisia Index decomposition (Ang & Liu, 2001), we statistically decompose annual changes in the emission levels from large stationary emission sources of four types of air quality pollutants, including sulphur dioxide, carbon monoxide, nitrogen oxides and particulate matters over the period 1990–2016. While most of previous decomposition studies have been decomposing emissions into scale, structure and emission intensity factors, a unique environmental dataset allows us to further decompose the emission per output effect into [i] the emission-fuel factor, [ii] the fuel-mix factor, and [iii] the fuel-intensity factor, yielding a 5-factor decomposition. We find that the largest drop in emissions of all four pollutants occurred up to 1999 when the emissions decreased cumulatively by 74 % at least. In this period, the firms faced new competitive environment and were exposed to strict new command and control regulation – as a result, negative emission-fuel factor was the key driver of the emission reduction. However, the fuel-intensity effect contributed most to reduction of SO_2, NOx and PM emission in the first 3 years after the Velvet revolution (1990-1992). Since 2008, activity, structure, fuel-intensity and emission-fuel factors have contributed to emission changes by similar magnitudes, but in different directions. In the last two years, the emission-fuel factor effect has become important again, as the large stationary emission sources were required to comply with new emission limits set by the EU Industrial Emissions Directive. In order to examine the effect of the key LMDI parameters on the decomposition outcome, we perform a sensitivity analysis to decompose SO_2 emissions on different numbers of effects (3-, 4- and 5-factors) and when different sectoral detail is assumed.

2.1. Introduction

Whether economic growth is pollution-reducing or a pollution intensifier has remained under dispute. IPAT-based literature[1], following a famous pioneering study by Ehrlich & Holdren (1971) and, then, *Limits to Growth* by Meadows, Meadows, Randers, & Behrens (1972), has tended to see **P**opulation growth coupled with growing per capita income (i.e. **A**ffluence) as the primary forces driving adverse environmental **I**mpacts, while **T**echnology has been considered to be mostly neutral. The IPAT approach has been criticized due to its pessimistic perspective on technological progress, a lack of behavioural response to adverse impacts, and the quality of data used in assessments (Carson, 2010).

The second stream of literature based on the Environmental Kuznets Curve hypothesis, following the pioneering 1991 study by Grossman & Krueger (1995), relies on the stylized fact that environmental quality tends to be positively, not negatively, correlated with income, especially in developed countries (Carson, 2010). An inverted-U shaped relationship between per capita income and environmental quality has been tested in many studies utilising simple or improved econometric models and datasets (see Cavlovic, Baker, Berrens, & Gawande (2000) or Dinda (2004) for a review). However, the Grossman & Krueger (1991) study clearly highlights the limitations of such analyses. It has been particularly recognized that it is just the reduced-form nature of the EKC model that limits the policy implications of its results. In other words, we cannot tell through which channel the level of income per capita affects environmental quality, nor we can reveal the extent to which the income factor contributes to changes in environmental quality.

Further, as a reaction to criticisms of the EKC, other statistical techniques have been developed to better understand the mechanisms of changes in energy use (or emission volume). In particular, researchers were looking for ways to quantify the impact of structural shifts in production and changes in sectoral energy intensity on total energy demand. Since then, decomposition analysis, and in particular the index-based decomposition analysis, has been used hand-in-hand with econometric analysis to understand trends and underlying factors of changes in energy use and emissions (Ang and Zhang, 2000). Compared to the reduced-form analysis performed in the most EKC literature, a decomposition analysis can identify the channels through which environmental quality is affected, as noted in Tsurumi & Managi (2010). Others have found that results based on a decomposition model have better statistical properties than the standard EKC specification (Stern, 2002). The main criticism of

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[1] The IPAT relates **I**mpact (e.g., pollution) to **P**opulation, **A**ffluence (proxied by per capita income), and **T**echnology, sometimes known as the Kaya identity.

decomposition analysis stemming from the fact that original approaches generated a residual term, which complicated interpretation of decomposition results, has been overcome by linking the decomposition to the Divisia index method.[2] Motivated by this discussion, we examine the main driving forces of significant reductions in the key air quality pollutants in a country that has faced dramatic political, economic and institutional changes over the past 29 years. In this paper, we conduct a Logarithmic Mean Divisia Index (LMDI) decomposition to examine the driving forces of change in air pollutants during the transition of the Czech Republic towards a market economy during the 1990s, becoming a member of the European Union in the 2000s, and complying with EU air quality and climate policy goals up to 2016. During the period analysed, the Czech economy evolved considerably in terms of its scale, structure, and institutions. The centrally-planned communist regime was replaced by a market economy governed by democratic institutions beginning with the Velvet Revolution of 1989. After a huge economic downturn due to the Revolution, it took the economy a decade to re-achieve its pre-market level. During the 1990s, the structure of the Czech economy changed significantly; industrial production declined from more than one third of GDP to one quarter, production in the mining and energy sectors decreased significantly, from 5% to 1.4%, and from 8% to 4% respectively, while market services, construction, trade and transport increased their outputs. The volume of air pollutant emissions fell tremendously, during 1990s (CENIA, 2005).

During the next decade, the Czech economy grew more than 40%, and since 2010 has increased by another 13%. These historical changes serve as a natural experiment, allowing us to investigate the key driving forces responsible for the huge drop in emissions of air pollutants. Our unique data set enables us to conduct a more refined index decomposition analysis (IDA) than prior studies have done. It also allows us to perform a set of sensitivity analyses of the LMDI method with respect to the number of decomposition factors used and the level of sector disaggregation.

We use a Logarithmic Mean Divisia Index to decompose the emissions of four air quality pollutants, specifically sulphur dioxide - SO_2, carbon monoxide - CO, nitrogen oxides - NO_x, and particulate matters - PM, into three to five factors: the activity effect, structure effect, fuel intensity effect, fuel mix effect, and emission-fuel intensity effect. The 5-factors decomposition enriches the existing literature, since the emission-fuel intensities have not been either available

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[2] Ang et al. (2002) defined four criteria for desired decomposition method that are factor-reversal, time-reversal, proportionality, and aggregation tests. Original approach based on Laspeyres index decomposition has been replaced by Divisia index decomposition mainly on the ground of a residual term that is generated by Laspeyres method.

or have been time invariant (based on average substance content) in all previous studies. In contrast to this commonly-used approach, our data contains information on the volume of each pollutant linked to each fuel used in the process, for instance, how much SO_2 is released per tonne of hard coal used in specific facility. This means that the emission coefficients we use in the analysis vary at the facility level as well as over time. Further, both emission volumes and fuel consumption are directly measured at the facility level. This provides more accurate data and a richer variation across facilities and time compared to emission values calculated based on time invariant chemical and technological parameters, which have been used in almost all previous studies.

The specific objectives of this paper are twofold: first, we identify the contribution of each of five factors affecting the emission level of four air pollutants in the Czech Republic during its transition and post-transition periods. Second, we perform a sensitivity analysis of the LMDI decomposition with respect to the number of factors and assuming different sector breakdowns of the Czech economy.

Institutional setting of the Czech Republic

Our analysis begins in the period of economic and political transformation in The Czech Republic[3] that started after the Velvet Revolution in 1989. The communist centrally planned economy was characterized by high energy and resource use accompanied by high pollution intensities due to a lack of environmental regulation and undercapitalization. In 1990, when economic and political transformation began, the Czech economy released around 16 tonnes of CO_2 per capita; an emission-output ratio six times higher than the ratio of the EU27 today. Because of high emissions of dust and sulphur released from insufficiently filtered power plants, the "Black Triangle" area (a region including northern Bohemia, southern Saxony and part of lower Silesia) was among the most polluted areas in Central Europe (Ürge-Vorsatz, Miladinova, & Paizs, 2006).

Already the first democratically elected government began to institute more environmental protections, and in order to comply with the Community Acquis of the EU, several policies to decrease pollution emission levels were introduced. The new Air Quality Act No. 309/1991 and related regulations, which required each existing large stationary emission source (power plants

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[3] The Czech Republic was part of Czechoslovakia until 31.12.1992. Our data represents gross value added, fuel consumption and emissions in the Czech Republic only.

and industrial factories) to comply with strict emissions limits until 1998, were the main drivers of the large reduction in emissions of air pollutants in the Czech Republic during the 1900s.[4]

Following this Act, emissions limits were set in 1991 and have since been strengthened several times (1992, 1995, 1997 and 2002). This command-and-control regulation drove a large reduction in emissions of air pollutants in the Czech Republic during the 1990s, particularly SO_2, NO_x, and PM.

Newly introduced economic instruments aimed to reduce emissions in the 2000s were quite ineffective due to low tax rates (in the case of energy taxes) or because of over-allocation of CO_2 allowances within the first phase of the EU ETS (Ščasný & Máca, 2009). As a consequence, as all large emission sources fulfilled their emission limits by 1999, the emission levels of air quality pollutants decrease only slightly over the next decade. Integrated permits introduced under *Integrated Pollution and Prevention Control* and concentration limits on pollutants in flue gas were the only truly effective instruments that regulated airborne emissions released from large stationary emissions sources in the 2000s.

The European directive on industrial emissions 2010/75/EU has induced further strengthening of airborne emission regulation. However, The Czech Republic has negotiated a transition period for implementation of this directive up to the end of 2016. This means most of the current large emission sources had time to fulfil new emission limits until the end of 2016.

We find that the leading driver in the decrease of emissions during the 1990s is the emission-fuel intensity effect, not the structure effect, which is consistent with the findings of other studies from developed countries and transition economies. Although, the fuel intensity effect is the most important up to 1992. The emissions abatement was introduced as a consequence of a new regulation on the concentration of air pollutants which required large emission sources to satisfy certain limits by 1999. It suggests firms adjusted their environmental behaviour by improving their end-of-pipe technology rather than by switching type fuel or by improving of energy efficiency. This finding shows that command-and-control regulation, as introduced in the Czech Republic in the 1990s, did not motivate firms to decrease the amounts of fuel used or to change the composition of the fuels, which would have required changing significant

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[4] Act No. 309/1991 applies at the federal level (Czechoslovakia). Act No. 389/1991 applies to the national level (the Czech Republic). Act No.309 determines the emissions limits and deadlines to fulfil the requirement, while Act No. 389 defines administration of the process and competences for the relevant authority, Česká inspekce životního prostredí (the Czech Environment Inspectorate).

amounts of their technology, but rather it motivated firms to decrease their emission levels by improving their end-of-pipe type measures without changing their technology.

We find that, after satisfying the emission limits requirements by 1999, large emission sources in the Czech Republic decrease their fuel intensity. This is the main driver that allows keeping their emissions on steady level between 1999 and 2007, despite the strong economic growth. Since 2008, the magnitude of activity, structure, intensity and emission-fuel intensity effects get closer to each other. In 2015 and 2016, the emission-fuel intensity effect becomes important again, as the large stationary emission sources has to comply with new strict emission limits based on the directive on industrial emissions.

This paper is structured as follows. The next section reviews related literature. Section 2.3 introduces the methodology and section 2.4 describes data. Section 2.5 presents the result of LMDI decomposition and provides a sensitivity analysis of LMDI decomposition with respect to the number of decomposition factors and sector aggregation. The final section concludes.

2.2. Literature Review

Decomposition analysis has been applied as a reaction to criticism of the Environmental Kuznets Curve hypothesis (e.g. Stern, Common, & Barbier,1996). Stern (2002) finds that results from the decomposition model have better statistical properties than the standard EKC specification, and notes that the basic EKC model can be considered a nested version of a decomposition model. Studies of statistical decomposition of emissions development differ in various ways: by the decomposition method employed, the number of factors of the decomposition studied, the geographical regions covered by the analysis, aggregation of the data, and object of the analysis.

First, there are two main streams in which the index decomposition analyses are applied: the Laspeyres/Paasche index methods and the Divisia index methods. The Laspeyres/Paasche index can generate large unexplained residuals, especially in the case of large magnitudes of changes in the factors. The refined Laspeyres index method (Sun, 1998) extends the Laspeyres/Paasche method, and can achieve perfect decomposition (no residuals). However, the refined Laspeyres index method allocates the unexplained residuals among the factors arbitrarily. On the other hand, the Divisia index method overcomes the problem of unexplained residual terms, i.e. it satisfies the factor-reversal property of decomposition indexes. In particular, the refined Divisia index method by Ang & Choi (1997), the new log-mean Divisia index (LMDI), possesses all three desirable properties — time-reversal, circular and factor-reversal — and is currently the best recommended, index decomposition method (Ang, 2004).

Secondly, the number of factors into which emissions are decomposed differs across studies. Most studies perform the three-factor decomposition, examining the effects of the scale, the composition, and the intensity (or technology) factor. A few studies decompose emissions into more than three factors. This, however, requires computations of emission volumes for each type of fuel. Without carbon capture technology, the emission-fuel coefficients for CO_2 can be derived quite straightforwardly by using the typical carbon content of fuel and specific oxidation parameters. Sun (1999) uses the time invariant emission-fuel coefficients following Torvanger (1991), and then conducts a 4-factor decomposition analysis on the emission of carbon dioxide for the 24 OECD countries for 1960-1995. Deriving the emission-fuel coefficients for other airborne pollutants requires more information. Viguier (1999) calculates the emission coefficients based on the parameters of the substance content of fuels, the fraction of substances removed by pollution abatement, and the fraction of substances retained in ash, respectively. However, neither of these two studies used directly measured emission volumes per fuel. In this paper, both the emission volumes and fuel used are measured and reported at facility level, which means the data contain a richer variation across plants and time.

Third, the studies differ in geographical coverage. Most studies investigate the former EU-15 countries (e.g. Löfgren & Muller (2010)) and Asian countries, mainly China (e.g. Lin & Long, 2016) with some studies focusing on the USA and Canada or selected OECD and IEA countries (see Ang & Zhang, 2000). Only a few applications of decomposition analysis in African countries and Central and Eastern European (CEE) countries exist, and in this respect, our study aims to contribute to filling this gap in the literature. Viguier (1999), above, is one of the few studies which analyses emissions in CEE countries. Further, Cherp, Kopteva, & Mnatsakanian (2003) analyse the quality of air in Russia over the period 1990-1999. They claim that in Russia, a structural effect works positively on production of emissions and the intensity effect influences emissions production negatively, as a result of more environmentally friendly technologies.

Last, but not least, most of the studies mentioned are focused on CO2 or GHG emissions only. Ang (2015) finds that application of IDA has evolved from a focus on energy consumption prior to 1990, to more often focusing on energy-related CO2 emissions since 2000. Ang (2015) denotes air pollutant emissions as one of new areas in which IDA is applied. In recent literature, we have found studies only from Asian countries – mainly China – that investigate airborne emissions. In particular, He, Yan, & Zhou, (2016); Y. Wang, Wang, & Hang, (2016); Yang, Wang, Zhang, Li, & Zou, (2016) focus on SO2 emission; Chang et al., (2018) investigate SO2 and NOx emission; Ding, Liu, Chen, Huang, & Diao, (2017); J. Wang et al., (2018) analyse NOx emission; and Lyu et al., (2016); Zhang et al., (2019) focus on PM emission.

Our paper follows up a couple of studies conducted in The Czech Republic that have not been published in scientific journals: Brůha & Ščasný (2006) apply the Laspeyres method for a 3-factor decomposition analysis on air pollutant emissions in the Czech Republic for the period 1992-2003. A shortcoming of this method is that it generates the residuals. Ščasný & Tsuchimoto (2013) and Tsuchimoto & Ščasný (2012) overcome the problem with the residuals and conduct 3-, 4-, and 5-factor LMDI decomposition analyses of air pollutant emissions for the period of 1995-2007. The added value of this paper is that we use extended and more detail datasets, paying special attention to consistent classification of firms into economic sectors. We extend the time span to 1990-2016, paying special attention to consistent classification of firms into economic sectors, and we use eight categories of fuel instead of five. As a results we are able to identify significant role of fuel intensity effect in 1990-1992 and capture the fuel mix effect for CO emission from 2008 to 2016.

2.3. Methodology

According to Ang (2004), the method of decomposition should be chosen such that it passes both factor and time reversibility and circular tests (Ang & Zhang, 2000). The most important test is factor reversibility. It requires perfect decomposition – meaning with no residual term. The conventional Laspeyres index is not recommended due to huge residuals.

The method used in Brůha & Ščasný (2006) satisfies the critical points above; but their method is based on a logarithmic approximation and therefore the results are sensitive to a large magnitude of change.

We apply the logarithmic mean Divisia index (LMDI) approach, which satisfies the property of perfect decomposition (Ang & Liu, 2001). "The LMDI approach involves variations in three different dimensions: by method (LMDI-I versus LMDI-II), by decomposition procedure (additive versus multiplication decomposition), and by aggregate indicator (quantity indicator versus intensity indicator)"Ang, (2015, p. 235). LMDI-I is consistent in aggregation (Ang & Liu, 2001) and perfect in decomposition at subcategory level (Ang, Huang, & Mu, 2009).We decide to apply the LMDI-I method based on recommendation of Ang, (2004, 2005) recommends LMDI-I method.

We follow Ang & Liu, (2007), who also resolve the problem with zero value observation by substituting the zero values with a very small number (e.g. between e^{-10} and e^{-20}). Both multiplicative and additive decomposition can be applied with equal results.

Following Ang (2005), the general index decomposition analysis identity is given by

$$E = \sum_i E_i = \sum_i x_{1,i} x_{2,i} \dots x_{n,i} \text{ ,}$$

(1)

where E is emission, x_n are factors contributing to changes in E over time and subscript i denotes a sub-category of the aggregate for which structural changes is to be studied. The emission changes from $E^0 = \sum_i x_{1,i}^0 \, x_{2,i}^0 \dots x_{n,i}^0$ in period 0 to $E^T = \sum_i x_{1,i}^T \, x_{2,i}^T \dots x_{n,i}^T$ in period T. The multiplicative approach decomposes the ratio between E^T and E^0:

$$D_{tot} = \frac{E^T}{E^0} = D_{x_1} D_{x_2} \dots D_{x_n},$$

(2)

The additive approach decomposes the difference between E^T and E^0:

$$\Delta E_{tot} = E^T - E^0 = \Delta E_{x_1} + \Delta E_{x_2} + \dots + \Delta E_{x_n}.$$

(3)

The subscript tot denotes the total relative or absolute change from period 0 to period T, respectively, and the right-hand side terms give the effects associated with the respective factors. The general formulae of LMDI-I for the effect of the kth factor are:

$$D_{x_k} = exp\left(\sum_i \frac{L(E_i^T, E_i^0)}{L(E_T, E_0)} ln\left(\frac{x_{k,i}^T}{x_{k,i}^0}\right)\right)$$

(4)

for the multiplicative approach and:

$$\Delta E_{x_k} = \sum_i L(E_i^T, E_i^0) \; ln\left(\frac{x_{k,i}^T}{x_{k,i}^0}\right)$$

(5)

for an additive approach. $L(a, b)$ is the logarithmic average of the two numbers, a and b.[5]

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[5] Specifically, $L(a, b) = \frac{a-b}{\log a - \log b}$, if a≠b, otherwise $L(a, b) = a$.

Since we analyse the emissions developments over the period of up to 27 years, when the magnitude of changes in emissions experiences a declining trend, we mainly focus on the additive LMDI-I, which has a more intuitive interpretation with regard to the magnitude of changes in emissions.

The standard, three factor IDA identity for emission level of the pollutants from industry is:

$$E = \sum_i E_i = \sum_i Q \frac{Q_i}{Q} \frac{E_i}{Q_i} = \sum_i Q S_i I_i,$$

(6)

where E is the total level of emissions from the industry, subscript i denotes sector, $Q(= \sum_i Q_i)$ is total industrial activity level, $S_i(= \sum_i Q_i/Q)$ and $I_i(= \sum_i E_i/Q_i)$ are, respectively, the activity share and emission intensity of sector i. The change in total emissions from time 0 to T is then:

$$\Delta E_{tot} = E^T - E^0 = \Delta E_{act} + \Delta E_{str} + \Delta E_{int}.$$

(7)

The subscripts act, str and int denote the effect associated with the overall activity level (scale), activity structure and sectoral emission intensity, respectively.

In addition to the emission level in each sector i, our data set contains information on consumption of fuel j in sector i and also on how much pollutant is emitted by each type of fuel: $E_{i,j}$. Using the richer information outlined above, we conduct not only the conventional three-factor decomposition analysis, but also four and five-factor analysis:

Four-factor: $$\Delta E_{tot} = E^T - E^0 = \Delta E_{act} + \Delta E_{str} + \Delta E_{int} + \Delta E_{em}, \qquad (8)$$

Five-factor: $$\Delta E_{tot} = E^T - E^0 = \Delta E_{act} + \Delta E_{str} + \Delta E_{int} + \Delta E_{mix} + \Delta E_{emf}. \qquad (9)$$

In four-factor decomposition, the subscripts act, str, int, and em denote the activity (scale) effect, structure effect, energy intensity effect, and emission coefficient effect related to total energy consumption, respectively.

In five-factor decomposition, the subscripts act, str, int, mix and emf denote the activity (scale) effect , structure effect, energy intensity effect, fuel mix effect and emission coefficient effect related to each individual fuel, respectively. The additive LMDI-I formulae for this five-factor emission decomposing between year 0 and T are:

$$\Delta E_{act} = \sum_{i,j} L(E_{i,j}^{T}, E_{i,j}^{0}) \ln\left(\frac{Q^{T}}{Q^{0}}\right),$$

$$\Delta E_{str} = \sum_{i,j} L(E_{i,j}^{T}, E_{i,j}^{0}) \ln\left(\frac{S_{i}^{T}}{S_{i}^{0}}\right),$$

$$\Delta E_{int} = \sum_{i,j} L(E_{i,j}^{T}, E_{i,j}^{0}) \ln\left(\frac{I_{i}^{T}}{I_{i}^{0}}\right),$$

$$\Delta E_{mix} = \sum_{i,j} L(E_{i,j}^{T}, E_{i,j}^{0}) \ln\left(\frac{M_{i,j}^{T}}{M_{i,j}^{0}}\right),$$

$$\Delta E_{emf} = \sum_{i,j} L(E_{i,j}^{T}, E_{i,j}^{0}) \ln\left(\frac{U_{i,j}^{T}}{U_{i,j}^{0}}\right),$$

(10)

where $L\left(E_{i,j}^{T}, E_{i,j}^{0}\right) = \frac{E_{i,j}^{T} - E_{i,j}^{0}}{lnE_{i,j}^{T} - lnE_{i,j}^{0}}$, $Q(= \sum_{i} Q_{i})$ is total industrial activity level, $S_{i}(= \sum_{i} Q_{i}/Q)$ and $I_{i}(= \sum_{i} F_{i}/Q_{i})$ are, respectively, activity share and energy intensity of sector i, $M_{i,j}(= \sum_{i,j} F_{i,j}/F_{i})$ represents the share of fuel j on total fuel consumption in sector i and $U_{i,j}(= \sum_{i,j} E_{i,j}/F_{i,j})$ is the emission-fuel intensity of fuel j in sector i.

2.4. Data

2.4.1. Emission and energy data

Emission and energy data used in this study was obtained from the Air Pollution Emission Source Register (REZZO – Registr emisí a zdrojů znečištění ovzduší).[6] The REZZO data on emissions attributable to stationary emission sources can be further divided into two broad categories. The first category covers emissions generated from fuel combustion, and the second covers emissions generated by various types of chemical reactions in technological processes. Our dataset is based on emissions generated from fuel combustion of facilities larger than 5MW of installed thermal capacity (termed REZZO 1).

For the fuel combustion processes in REZZO 1 facilities, our data set contains unique information about how much emissions are produced by which type of fuel, e.g., how much SO_2 is generated by the combustion of brown coal. While our database on combustion processes allows us to derive emissions per fuel type used for each unit, the emissions from technological processes do not contain information on the attribution of a specific fuel. That is why we particularly focus on emissions generated by REZZO 1 combustion processes (R1comb) in this paper.

The emissions released from the combustion processes of large stationary emissions sources (R1comb) represent a large share of the total aggregate level of emissions, about 80% of total SO_2 and NO_x emission over almost the entire period. The share of particulate matters (PM) from R1comb on total PM decreases across time due to a strict abatement introduced in large sources. Large combustion sources contribute only small amounts to emissions of CO, 5% to 8%. The heat and power sector (NACE rev.2 code 35) represents the majority of fuel consumption and emissions production in our dataset (R1comb) – it represents 70-80% of NOx and SO2 emissions with increasing trend, its share PM emissions decreases from initial 52 %

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[6] The REZZO database, maintained by the Czech Hydro-Meteorological Institute, distinguishes four broad categories of emission sources in which data are stored: REZZO1 and REZZO2 include large and medium-sized emission sources, grouped by their thermal output amounts which are larger or smaller than 5MW respectively; REZZO3 reports the emissions released by local units, including households and area sources, while R4 reports emissions from mobile sources. In the case of large emission sources (REZZO1), data are gathered at the facility level. Data for medium-sized sources (REZZO2) are reported at the firm level.

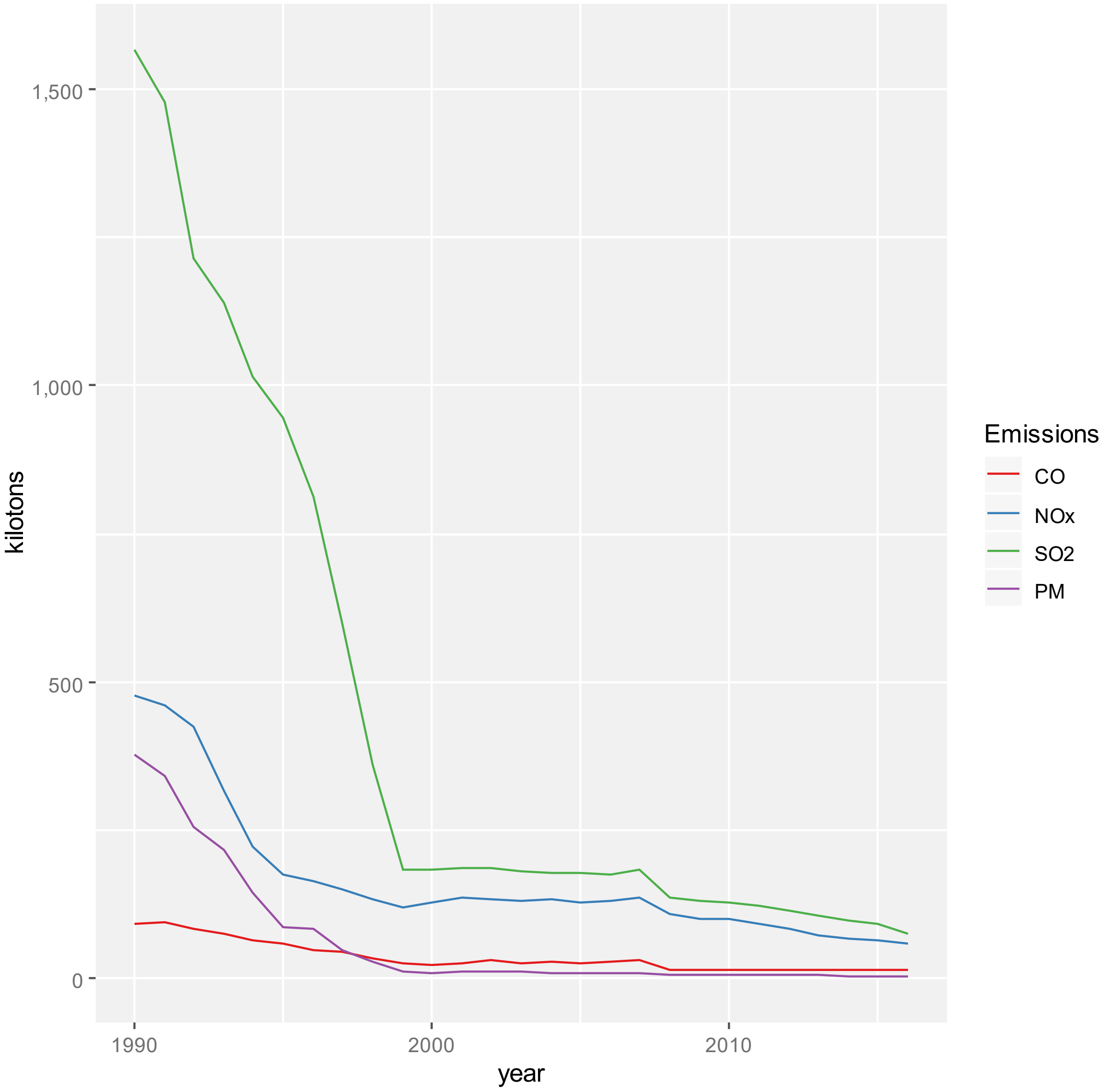
to 33% in 1994 and then increase up to 87 % in 2014. The heat and power sector´s share on fuel consumption on our dataset increases from 65 % to approximately 80 % since 2011.

Figure 1 shows development of emissions levels of CO, NOx, SO2 and PM in our data set from 1990 to 2016. There is an inconsistency between 2007 and 2008. The NACE classification changed from NACE rev.1 to NACE rev.2 in this period. The NACE rev.2 offers more detail than NACE rev.1 and as a consequence, a part of emissions reported in the R1comb database shifted to purely technological processes, while a part of the fuel consumption remained in R1comb – our datasets. As a result, we can observe a drop in all emissions between these two years that is reflected in energy intensity and emissions factor effects. Therefore, we do not interpret the change of emission levels between 2007 and 2008.

We can identify three periods with different patterns of emissions development. In the first period, from 1990 to 1999, all emissions dropped rapidly – on average CO, NOx, SO2 and PM by 14, 14, 21 and 32 percent per year. In the second period, from 2000 to 2007, emissions varied around constant levels or even increased slightly. In the last period, from 2009 to 2016, CO emissions varied, and increased on average by 2 % per year, and NOx, SO2 and PM emissions declined again.

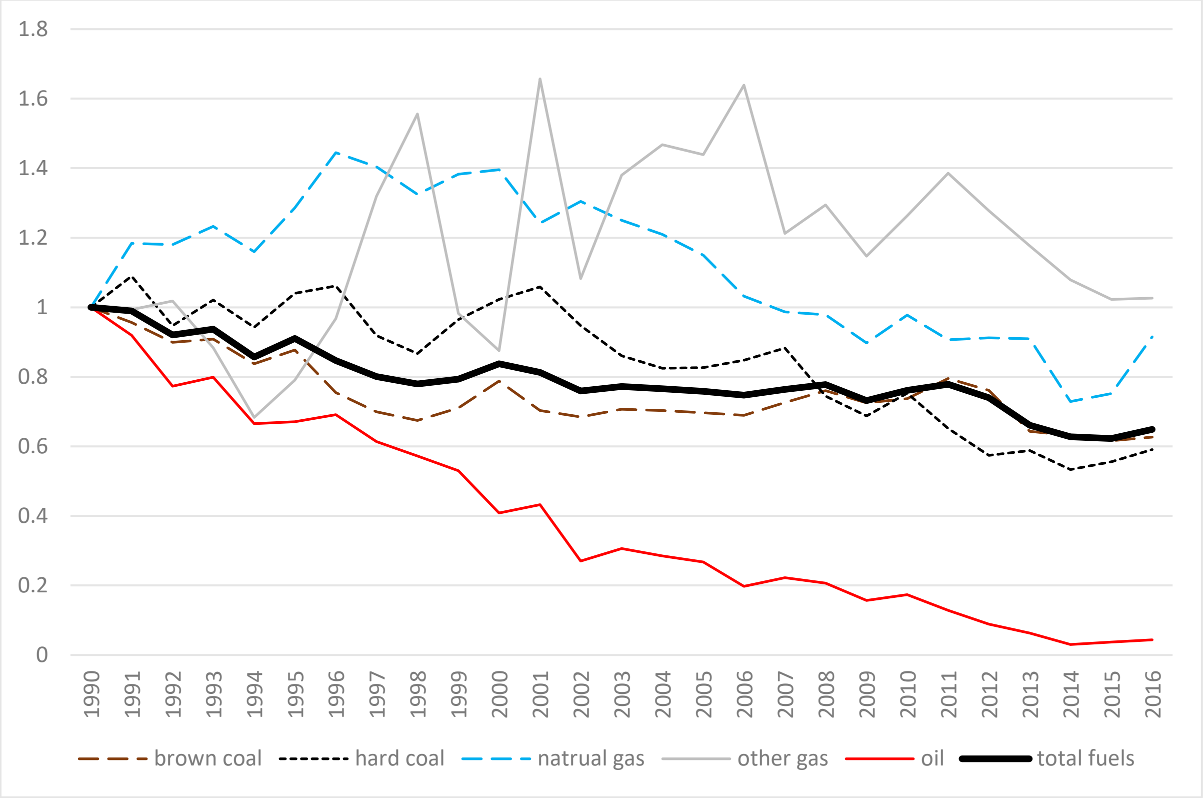
SO2 emissions experienced the largest absolute decrease across the whole period, decreasing from 1575 kt in 1990 to 74 kt in 2016. Therefore, we present the sensitivity analysis of LMDI decomposition on SO2 emissions in section 2.5.2.

Figure 1 Emission levels of CO, NOx, SO2 and PM, 1990–2016 for R1comb [kt]



We conduct the decomposition for eight categories of fuel: (1) brown coal, (2) biomass, (3) biogas, (4) hard coal, (5) natural gas, (6) oil, (7) other gases and (8) other solids. Figure 2 depicts relative development of total fuel consumption and five main fuels in in our dataset from 1990 to 2016. During this period, total fuel consumption has decreased by more than 35%.

Figure 2 Fossil fuels and total energy use , 1990–2016 for R1comb (1990 level = 1.0)



Note: The figure does not depict development of biogas, biomass and other solid fuels, they are included in total fuels, since use of these fuels was very low in the 1990s and grow then rapidly after 2000. Biogas use has started to be reported since 1997. In 2016, use of biogas, biomass and other solid fuels is 21-, 10- and 6-times larger than in 1990 or 1997, respectively.

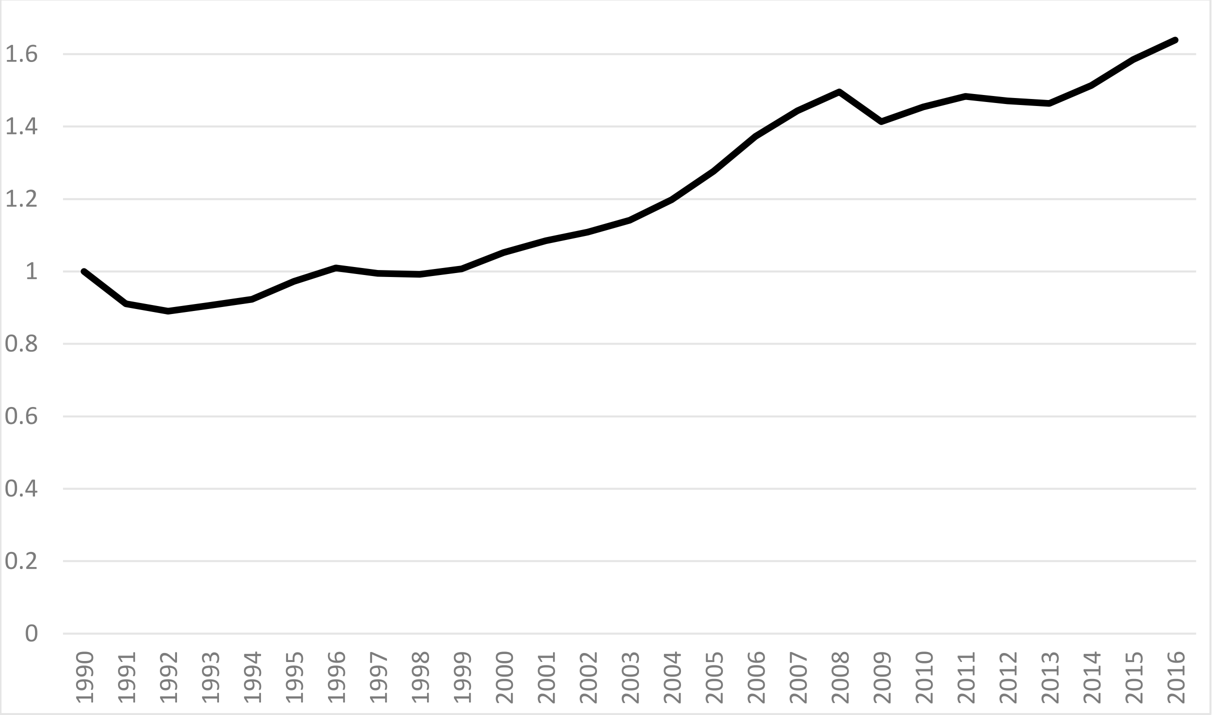
2.4.2. Activity data and aggregation of sectors

We use the Gross Value Added (GVA) as a proxy for economic activity. The GVA is obtained from the Supply and Use Tables (SUT) conducted by the Czech Statistical Office. Unfortunately, the sector classification in SUT is not constant in time. From 1990 to 1994, SUT are reported only in the simple structure of a NACE rev.2 sector classification (38 sectors) and only since 1995 have the SUT been reported in full level 2 NACE rev.2 classification (88 sectors). The GVA is expressed in real 1995 prices calculated based on the current and previous year's prices in the SUT.

The REZZO database contains information on the economic sector of facilities in NACE rev 1.1 till 2007 and only since 2008 in NACE rev.2 classification.

In order to compile a consistent dataset, we have to convert all sector classifications into the same classification structure. There is no one to one match between NACE rev.1.1 and NACE rev.2. First, we convert the REZZO database to aggregation of NACE rev.2 classification. As a result, we have a dataset aggregated to 44 sectors covering all large combustion sources in R1comb, consistent from 1995 to 2016. Second, we combine this 44 sector aggregation with the simple structure of NACE rev.2. and obtain a dataset aggregated to 26 sectors from 1990 to 2016. Figure 3 depict the relative development of Czech GVA from 1990 to 2016. During this period, the GVA in constant prices of 1995 has increase by almost 64 %.

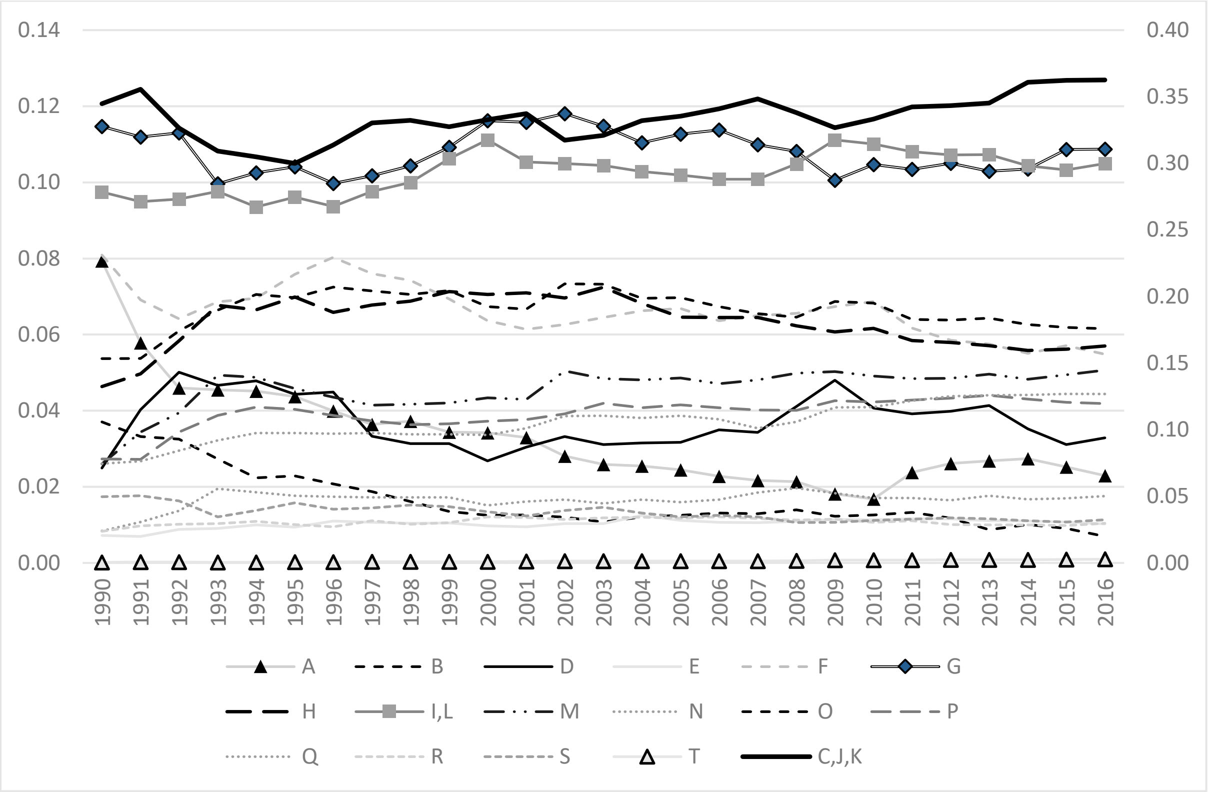
Figure 3 Gross value added, 1990–2016



We apply the LMDI decomposition to both datasets and also aggregate our dataset to 18 sectors to test the effect of sectoral aggregation on the precision of the LMDI method. Figure 4 depicts shares of economic sectors in 18 sector aggregation on total GVA from 1990 to 2016. Share of heat and power sector (D) involves counter-cyclically. Agriculture (A) and Mining and quarrying (B) from 8 to 2 and from 4 to less 0.7 percentage share on total GVA, respectively. Other sectors vary around their initial values. Figure 5 focuses on the C,J,K sector that has share of approximately 35 % GVA and depicts shares of its subsectors on total GVA.

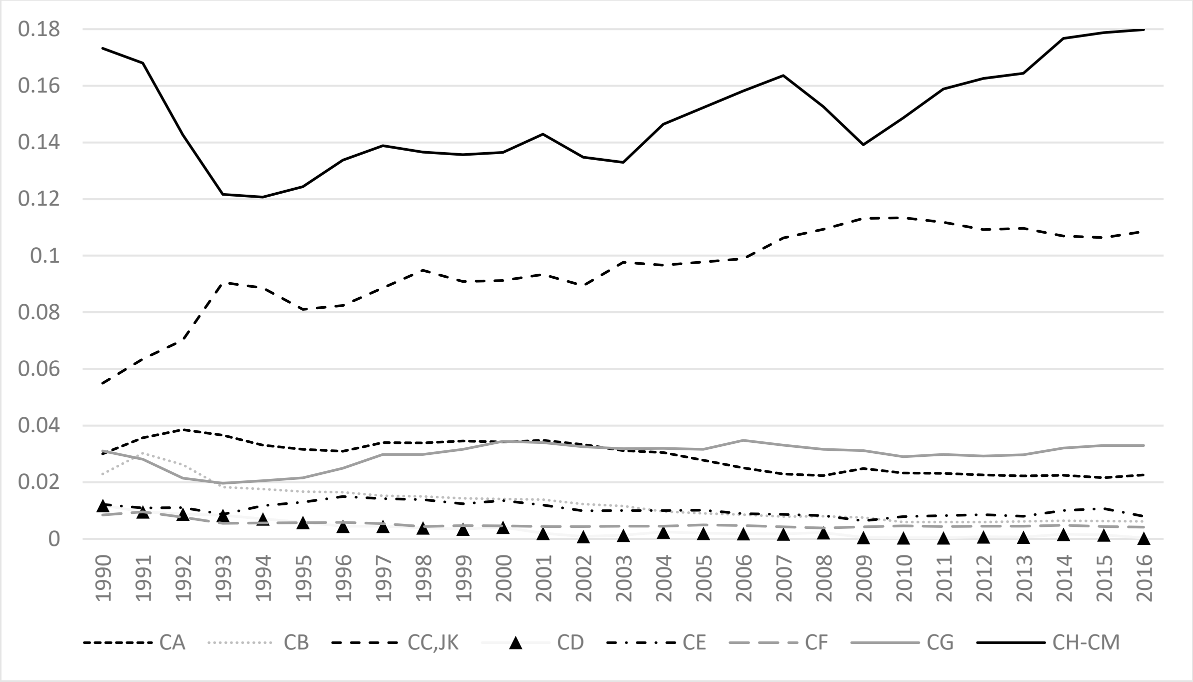
Table 6 in Appendix A provides the sectoral aggregation in all three cases.

Figure 4 Share of sectoral GVA on total GVA, 1990–2016 (18 sectors)



Note: C,J,K sector (NACE codes 10-33 and 58-66) are on the right axis.

Figure 5 GVA share of C,J,K subsectors on total GVA, 1990–2016



2.5. Results

We apply the 5-factor LMDI decomposition in order to analyse the five underlying factors of air quality emissions in the Czech Republic from 1990 to 2016. Specifically, we quantify the amounts each of these five factors (scale, structure, fuel intensity, fuel-mix and emission-fuel intensity) were contributing to changes in the volumes of these emissions over this period. Then, we perform sensitivity analyses of the LMDI decomposition with respect to the number of decomposition factors (3F and 4F compared to 5F) and sectoral breakdown of the economy.

The decomposition is always performed on a year-by-year basis, though we report the results for a particular year if a cumulative effect is reported for a period. We also note that fuel use and emissions are measured for the large emission stationary sources and for combustion processes, setting aside emissions stemming from technological processes, medium-size and small stationary emission sources and mobile sources.

Due to a revision in NACE classification, the data are not fully consistent around 2007-2008.[7] As a consequence of this inconsistency, there are visible sharp hikes in the 2008/2007 annual

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[7] As a consequence of the NACE revisions, some facilities were reclassified into a different economic sector and/or moved from the category of stationary emission sources combusting fuels (addressed in this paper) to sources

changes in all figures below. Due to this inconsistency in data, the 2008/2007 annual changes cannot be compared and readers should overlook them.

2.5.1. Five factor decomposition of air quality emissions for 1990–2016

This section provides the results of the 5F LMDI decomposition of SO2, NOx, PM and CO emissions performed for each year for the period of 1990–2016. This decomposition is performed with the economy breakdown into 26 economic sectors and eight different types of fuels. This means the decomposition works with 26 x 8 different emission-fuel intensities gathered for each year. Since the economic data are available in finer sectoral disaggregation from 1995 only, the LMDI decomposition with a 44 sector-breakdown can be carried out from 1995 on. These results are provided in the Appendix. How finer sectoral breakdown affected the decomposition outcome during the period 1996–2016 is therefore discussed in next subsection.

Figures 6–13 display the results from the 5F LMDI decomposition, in which we show the contributions of factors to emission changes in tonnes (on the left, in figures with even numbers) and then in percentage points (on the right, in figures with odd numbers). In each of the figures it is visible that, although the patterns of emission reductions and their drivers vary across the four pollutants analysed, there are two factors that are responsible for the largest portion of emissions reductions of each pollutant during nearly the entire period analysed. These two factors are the fuel intensity and the emission-fuel intensity.

Table 1 provides the results for the three periods (1990-1999, 1999-2007 and 2008-2016), but even here the decomposition is always performed on a year-by-year basis.[8] From left to right, we report the total changes that occurred before the end and the beginning of each particular period in kilotons and percentages. For instance, emissions of SO2 were reduced by 1,391 kt between 1990-1999, which amounted to a reduction of 88 %. In following period of 1999 -

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releasing emissions from technological processes or to small emissions sources (neither of which is considered in this work).

[8] As Löfgren & Muller (2010) emphasized, "summing the effects of one factor over all years usually does not reveal a reliable overall effect of the factor in question" (Löfgren & Muller, 2010, p. 230). Hence, a decomposition that is based on the first and last years of a certain period exhibits similar problems as summing the effects of one particular factor over years. It implies that "results from decomposition analysis of changes over several years based on the first and the last year only or reporting sums over all years should be used very cautiously" *(ibid.)*. We therefore present such results only in the Appendix A, Table 4 and Table 5.

2007, SO2 emissions were stable. In the 2008-2016 period, these emissions decreased further, by about 61 k, amounting to a 45 % reduction. The remaining five columns display overall whether and how much a given factor contributed more positively (increasing emissions) or negatively (decreasing emissions). Again, in the case of SO_2 emissions and for the first period (1990-1999 with 9 year-by-year changes), there were one more positive effects of the scale factor than negative (+1). For the same period and the same pollutant, the fuel mix factor affected emissions seven times more negatively than positively, and emission-fuel intensity constantly reduced emissions (i.e. the effect of this factor was always negative).

Table 1 Cumulative emissions change by period and indication of LMDI effects impacts

Pollutant	Period	Change (kt)	Change (%)	Activity	Structure	Fuel intensity	Fuel mix	Emission-fuel
CO	1990-99	-68.2	-73.8%	1	-3	-5	-5	-5
	1999-07	5.7	23%	8	-2	-6	0	0
	2008-16	3.9	29.3%	2	0	-2	2	2
NOx	1990-99	-358.5	-74.9%	1	-1	1	-3	-7
	1999-07	15.0	12.5%	8	2	-4	0	2
	2008-16	-52.2	-46.9%	2	0	0	-2	-8
PM	1990-99	-369.3	-96.9%	1	1	-1	-9	-7
	1999-07	-3.0	-25.6%	8	0	-4	-2	0
	2008-16	-1.8	-37.9%	2	0	0	-6	-4
SO2	1990-99	-1391.4	-88.3%	1	-1	1	-7	-9
	1999-07	-1.0	-0.6%	8	2	-4	0	0
	2008-16	-60.6	-44.9%	2	0	2	-4	-4

Note: In the last five columns we indicate how many times a given decomposition factor was either positive (increasing emissions), or negative (reducing emissions). The indicator is a sum of positive contributions (+1) and negative contributions (-1) across all years in the given period. For instance, zero indicates there were the same number of years with positive and negative direction of the factor effect for the given period. The decomposition is always performed on a year-by-year basis, so there are nine effects (one for each year) for the period 1990-1999, eight effects for 1999-2007 and another eight effects for 2008-2016

Table 1 clearly shows that the largest drop in emissions of all four pollutants occurred in the first period, from 1990 to 1999, when the emissions decreased by at least 74 %. In this period, the emission-fuel intensity factor was dominant in reducing emissions, followed by the fuel-intensity effect and the fuel-mix effect. In contrast, the activity and structure effects had positive impacts on emissions growth.

In the second period, from 1999 to 2007, emissions paths followed different patterns and even trends. Strong economic growth in this period resulted in a strong positive activity effect. The structure and fuel mix effects went in the same direction for all pollutants, but their effect was significantly lower than the activity effect. The fuel-intensity factor was the only negative one, and it reduced all four pollutants in this period. Thanks to its effect, overall emissions did not rise during this period. The effect of the emission-fuel intensity factor was both positive and negative during this period, as shown in Figure 7, Figure 9, Figure 11 andFigure 13. The emission-fuel intensity reduced emissions of PM, its effect was almost neutral for SO2 and it increased emissions of NOx and CO. Over the second period, CO and NOx emissions increased by 23 and 12 percent, while emissions of PM and SO2 decreased by 26 and 1 percent, respectively.

In the last period, from 2008 to 2016, the activity effect is positive, but its magnitude is lower than the effects of the other factors. The structure and fuel-intensity factors contributed negatively or positively at different magnitudes. As in the first period, the emission-fuel intensity is the most important factor in reductions of SO2, NOx and PM emissions. Overall, SO2, NOx and PM emissions followed a decreasing trend in this period. Emissions of CO rose and fell, but overall CO emissions rose, following the trend since 1999. In this case, while the activity, fuel-intensity and emission-fuel intensity factors mainly contributed to CO emissions increases, the fuel mix worked mainly in the opposite direction.

The magnitude and direction of the effect due to each factor is displayed in detail in figures 6–13. SO_2, NO_x and PM emissions shared a common decreasing trend over the whole period when the fuel mix effect was relatively low (up to -4, -2 and -6 percent, respectively) compared to the effects of other factors. CO emissions started at the lowest initial value of all four pollutants (see Figure 1). Their decline was relatively low in magnitude compared to other pollutants, and these reductions were realised mostly before 2000. Since then, emissions of CO rose and fell with the diverse directions of the effect of each factor, but the emission-fuel intensity was primarily responsible for reducing CO emissions, particularly before 2000.

In the first years after 1989, the Czech economy changed considerably in terms of its structure, and reduced its energy intensity. Still, the structure effect was very strong and positive, leading to increases, not decreases, in emissions of SO_2, NO_x and PM during the early years of economic transformation (1990-1992). Fuel intensity and activity factors worked in opposite directions in the first years after the Revolution, reducing emissions from large stationary sources by relatively large amounts and percentages. Emission-fuel intensity played a dominant role in reducing SO_2 and PM emissions until 1999 and 2000, respectively, due to installations of abatement technologies as a consequence of air emission control regulations introduced at the beginning of the 1990s. Between 2000 and 2014, the importance of the emission-fuel intensity factor lost its dominancy in reducing SO_2 and PM emissions, while the roles of fuel-intensity, structure and activity factors became at least as important as the emission-fuel intensity effect.

Figure 6: 5 factor decomposition of SO2 emission from 1990 to 2016 (t)

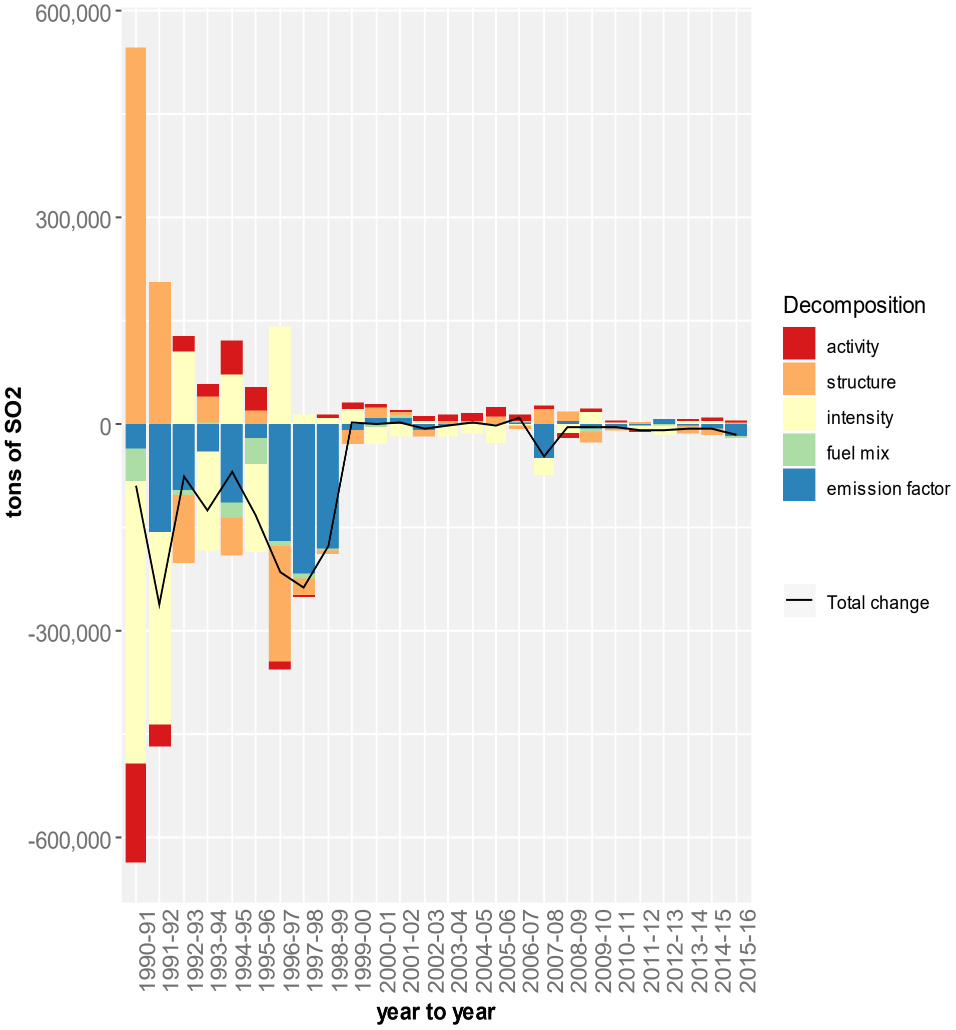


Figure 7: 5 factor decomposition of SO2 emission from 1990 to 2016 (percent)

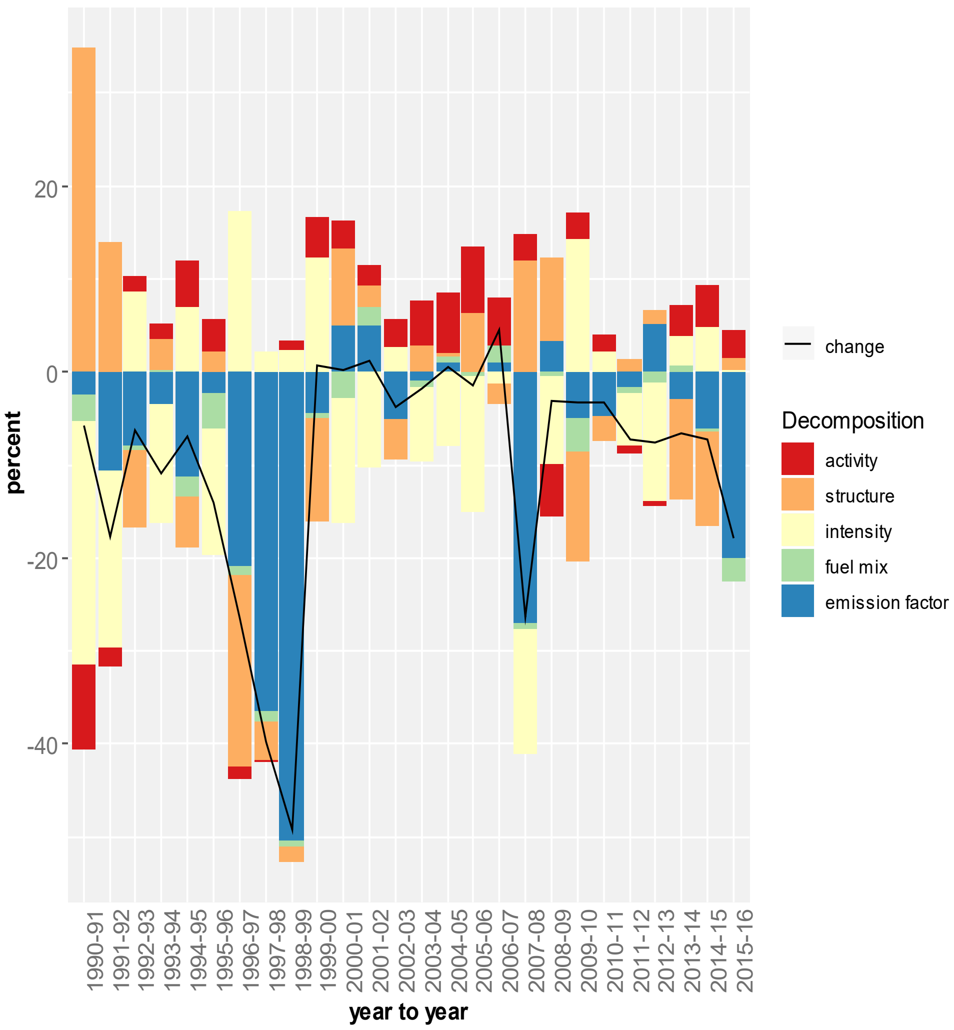


Figure 8: 5 factor decomposition of NOx emission from 1990 to 2016 (kt)

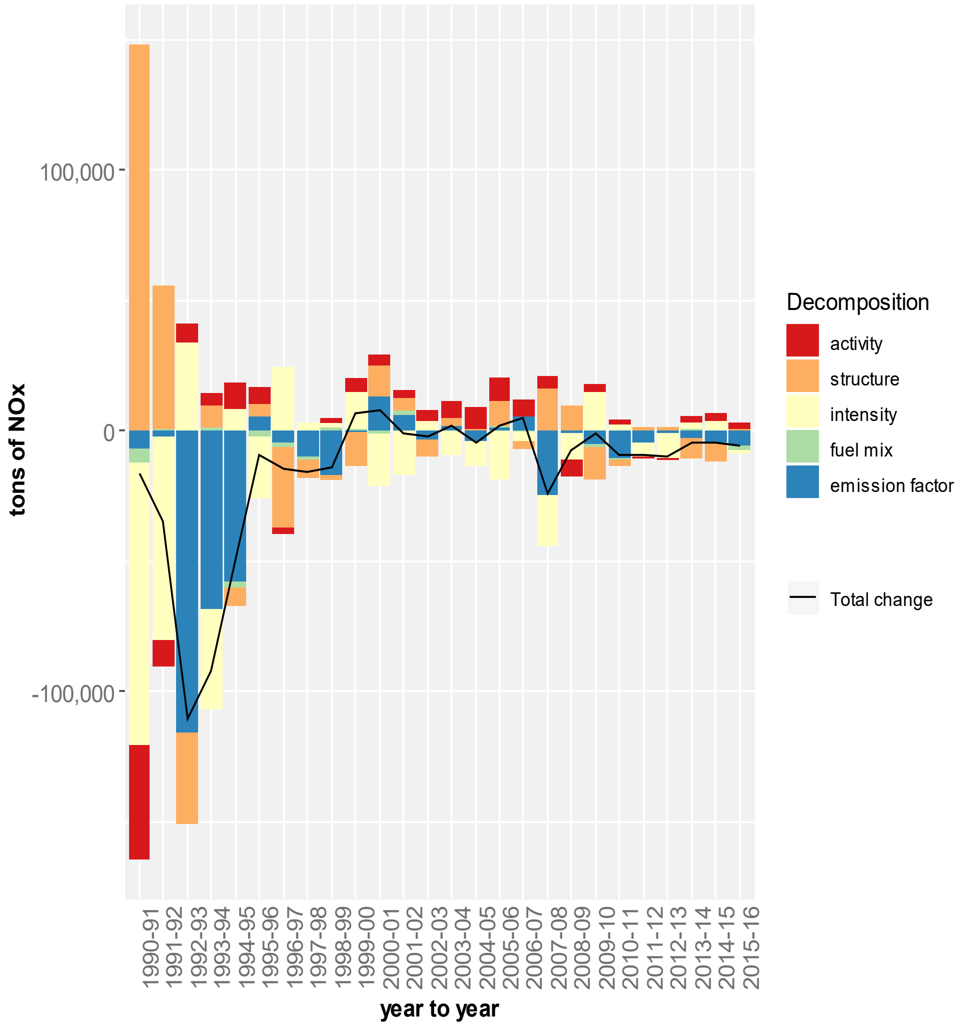


Figure 9: 5 factor decomposition of NOx emission from 1990 to 2016

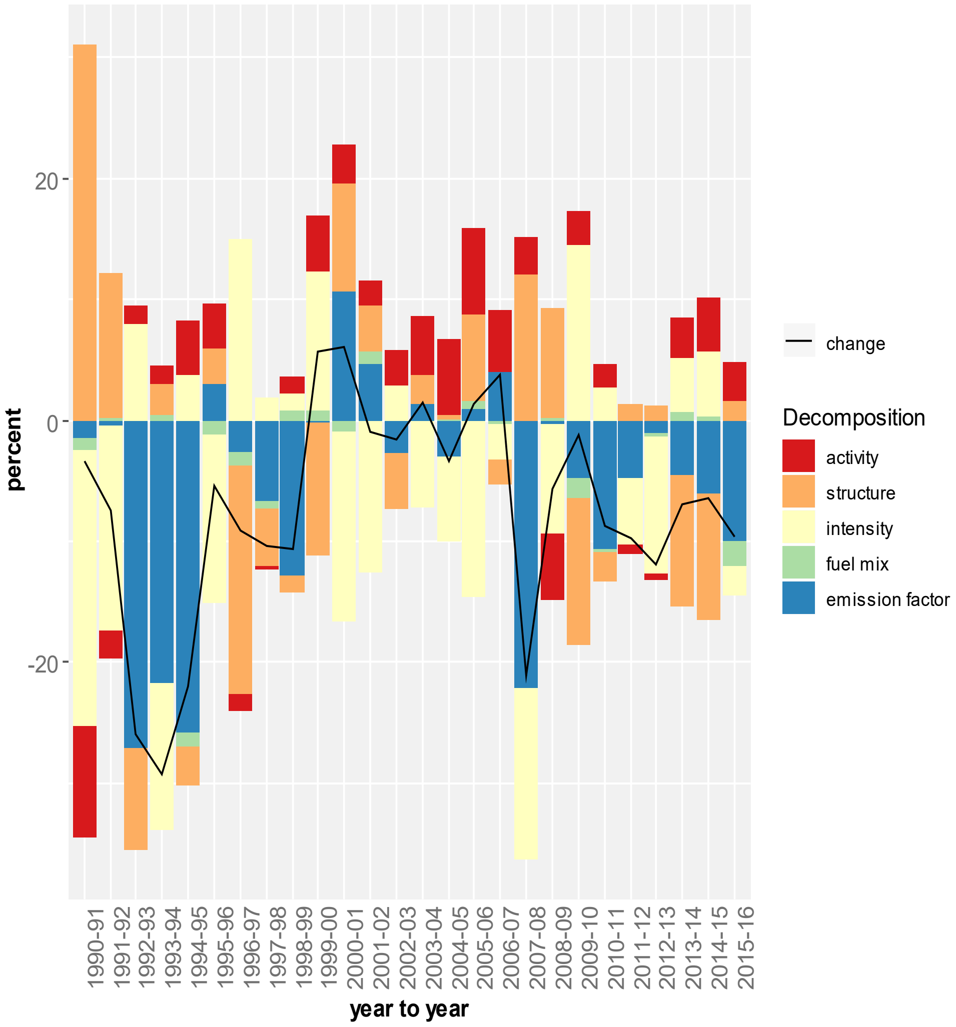


Figure 10: 5-factor decomposition of CO emission from 1990 to 2016 (kt)

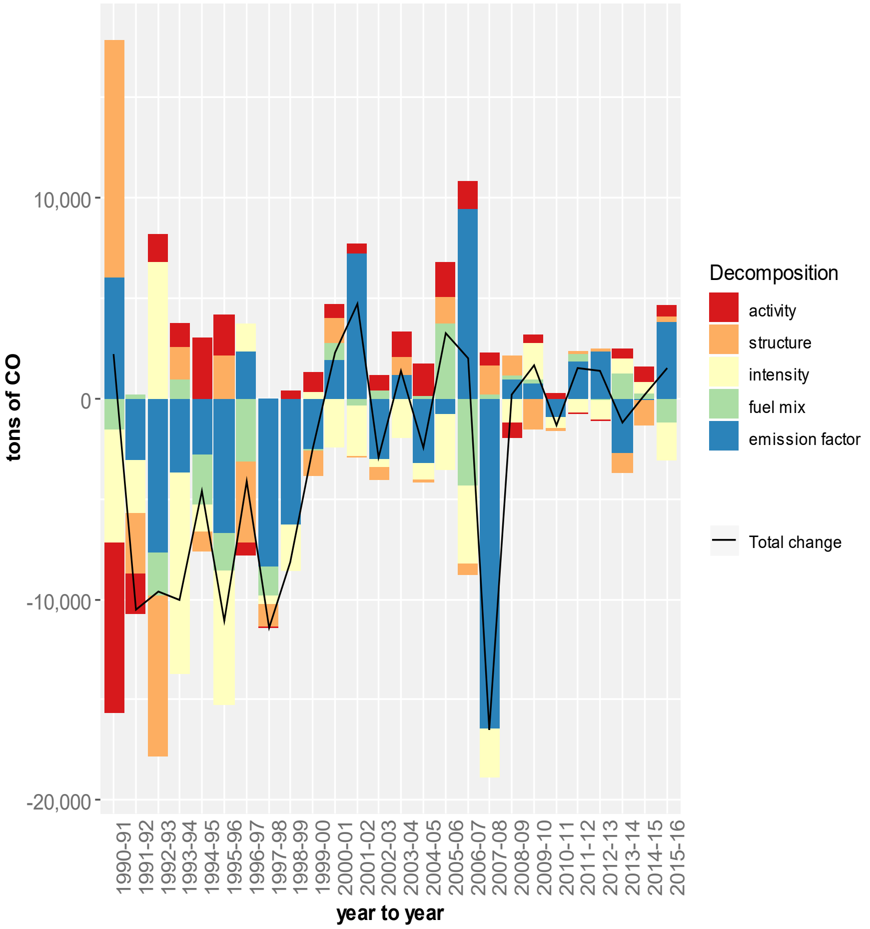


Figure 11: 5-factor decomposition of CO emission from 1990 to 2016

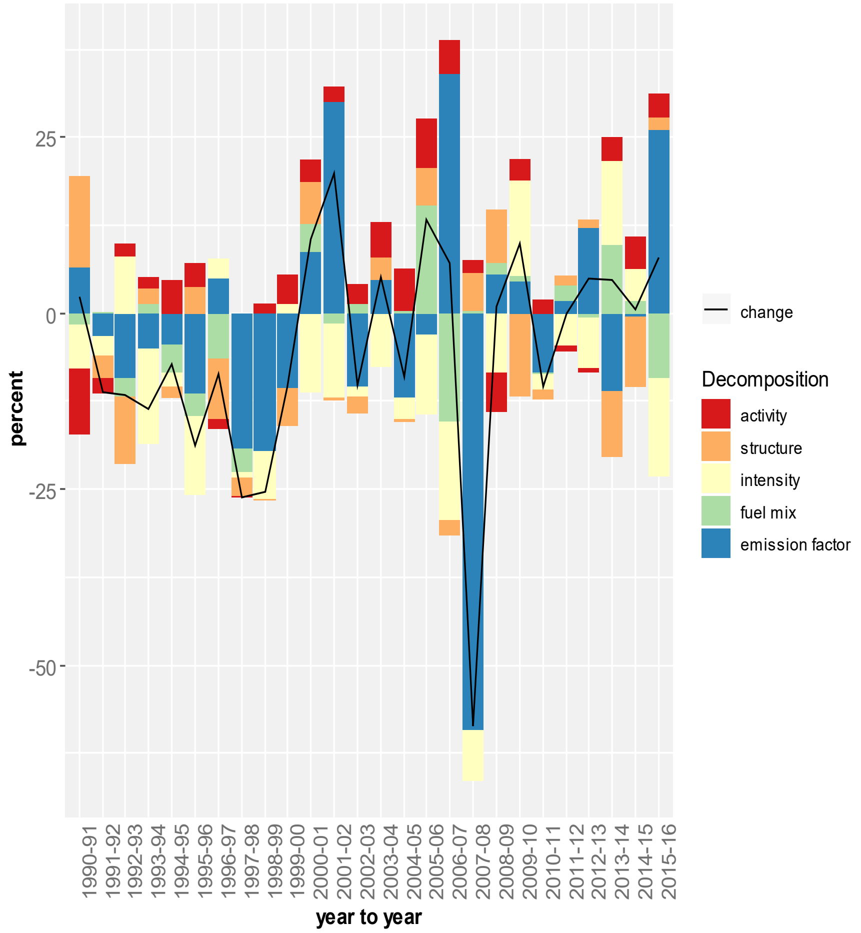


Figure 12: 5-factor decomposition of PM emission from 1990 to 2016 (kt)

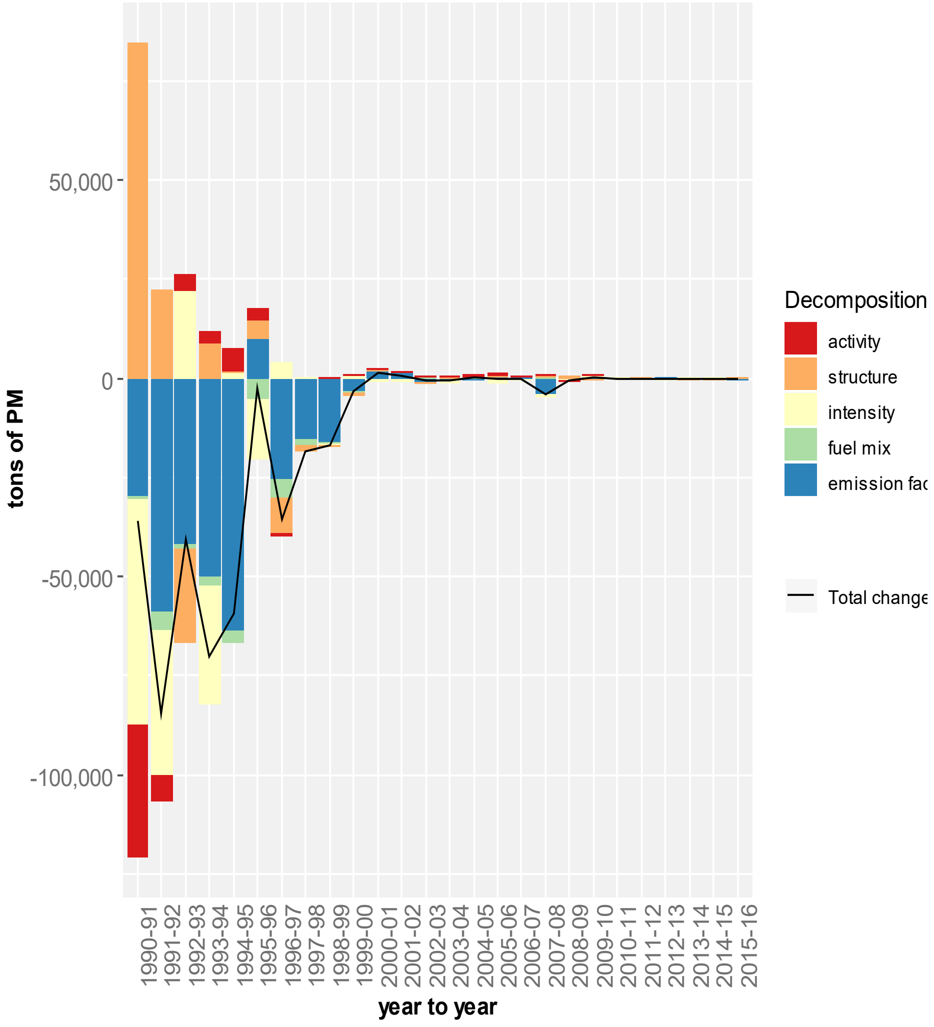


Figure 13: 5-factor decomposition of PM emission from 1990 to 2016

2.5.2. Sensitivity analysis of LMDI decomposition with respect to the number of decomposition factors and sectoral aggregation

We perform sensitivity analyses of LMDI decomposition on individual years in the period between 1995 and 2016, when we have the most detailed dataset of 44 sectors. We focus on the differences between the decompositions with respect to the number of decomposition factors and sectoral aggregation here, and present all figures in percentages.

2.5.2.1. Sensitivity analysis of LMDI decomposition with respect to the number of decomposition factors

Figure 14, Figure 15, and Figure 16 provide the results of 3-factor, 4-factor and 5-factor decomposition of SO2 emissions for 44 aggregated sectors from 1995 to 2016, respectively. Both changes in emissions levels and the contribution of each factor are displayed in percentages.

Most literature applying LMDI decomposition performs a 3-factor decomposition. This distinguishes the activity effect of the whole economy, the structure effect and the emission intensity effect. The emissions intensity effect is the main driver of SO2 emissions reduction in the period from 1995 to 2016 (in sum and in 14 cases of 21), followed by the structure effect. The activity effect, on the other hand, is positive in 17 of 21 cases.

The emissions intensity effect captures three emissions abatement options together, i.e. it captures abatements through end-of-pipe technology, fuel switch and technological and/or product changes that can affect the energy intensity of production. This factor thus indicates the effects of the environmentally friendliness of production without distinguishing further through which channel the emissions were abated. Although these three channels can be either combined or counteract each other – as is clear from the emissions changes from 1996 to 1997 (second column in the figures) when the positive effects of energy intensity are outweighed by negative effects of emissions factor (Figure 15 and Figure 16) and partly by fuel mix factor too (Figure 16).

Figure 14 3-factor decomposition of SO_2 emission from 1995 to 2016 (44 sectors)

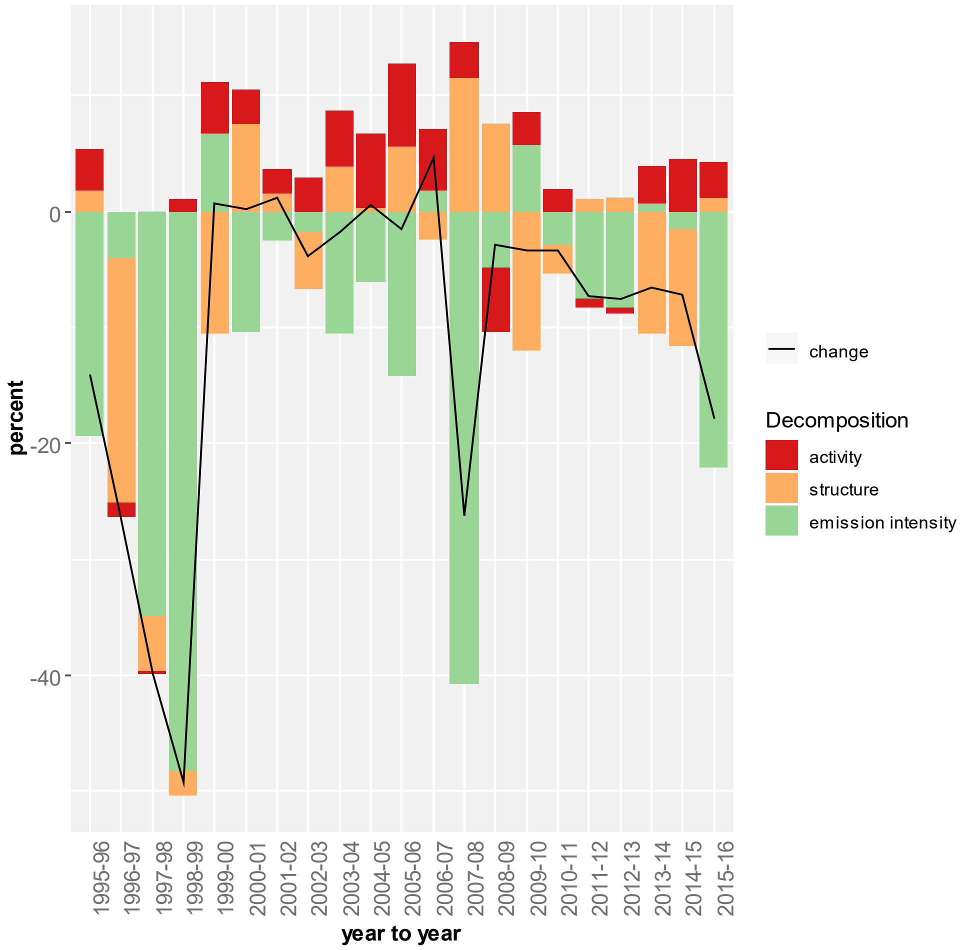


Figure 15 : 4-factor decomposition of SO_2 emission from 1995 to 2016 (44 sectors)

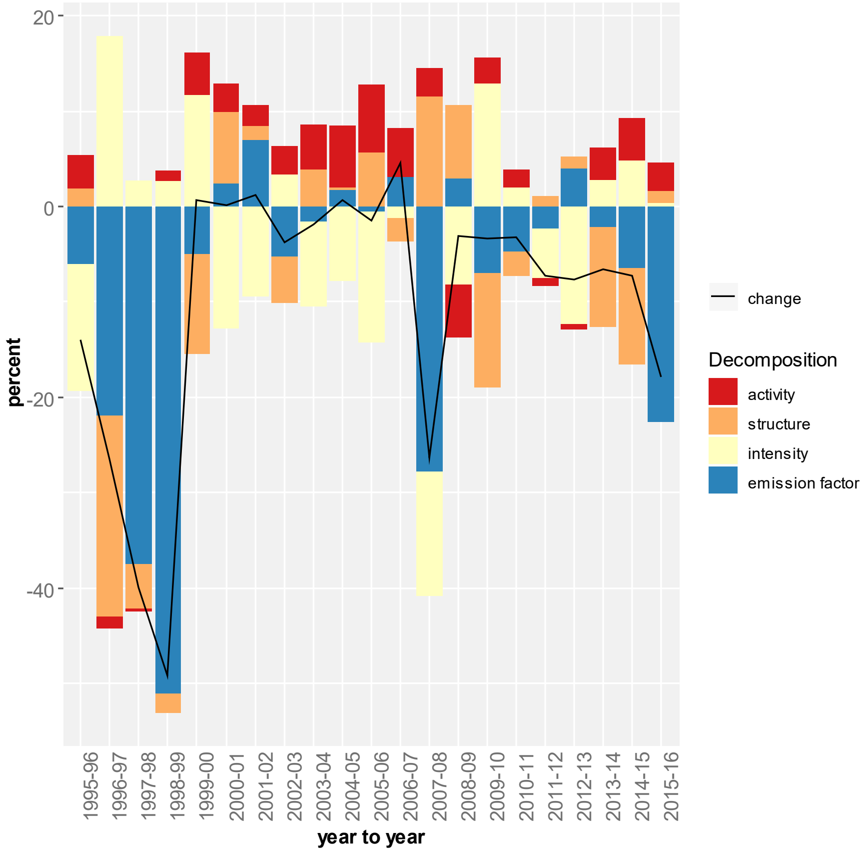


Figure 16 5-factor decomposition of SO_2 emission from 1995 to 2016 (44 sectors)

The 4-factor decomposition allows us to understand the underlying drivers of the emissions intensity effect – i.e. the energy intensity effect, the emissions factor effect aggregated for total energy consumption. We can see the energy intensity effect on SO2 emissions was positive ten times and negative ten times between 1995 and 2016, but over this period, the reductions in the energy intensity of the Czech economy helped to reduce SO2 emissions overall.

The 5-factor decomposition goes one step further and decomposes the emissions factor aggregated for total energy consumption to fuel mix effect and the emissions factor effect related to consumption of individual fuels. The fuel mix effect captures the effect of a change in fuel type on emissions. The emissions factor effect captures changes in the quality of fuel within the particular fuel (e.g. shift to coal with low content of SO2) and changes in technologies – mainly the introduction of end of pipe abatements – where the later channel of emissions reduction is dominant.

Figure 16 shows the new information on the role of fuel type changes on SO2 emissions, compared to the 4-factor decomposition. The fuel mix effect supports the emissions factor effect in 15 of 21 years analysed, but is always lover in absolute terms than the emissions factor effect.

Thanks to the definition of LMDI decomposition, adding fuel specific dimension – in the 5-factor decomposition – affects not only the last factor that is decomposed, but has a slight impact on the other effects as well (e.g. $\sum_{i,j} L(E^T_{i,j}, E^0_{i,j}) \ln\left(\frac{Q^T}{Q^0}\right)$ is not equal to $\sum_i L(E^T_i, E^0_i) \ln\left(\frac{Q^T}{Q^0}\right)$). Table 2 compares the activity, structure and intensity effects in 5-factor LMDI and with 3- and 4-factor LMDI decomposition effects. Introduction of fifth factor and the new dimension of specific fuel decrease all other LMDI effects in most cases.

Table 2 Impact of additional dimension in 5-factor LMDI on activity, structure and intensity effects

Factors compared:	5/3		5/4		
Effect	Activity	Structure	Activity	Structure	Intensity
1995-96	-0.2%	-0.5%	-0.2%	-0.5%	-0.2%
1996-97	-0.5%	-0.4%	-0.5%	-0.4%	-0.5%
1997-98	-0.2%	-0.1%	-0.2%	-0.1%	0.7%
1998-99	-1.0%	-3.1%	-1.0%	-3.1%	3.1%
1999-00	-0.4%	-0.1%	-0.4%	-0.1%	0.0%
2000-01	-0.5%	-0.2%	-0.5%	-0.2%	0.4%
2001-02	-0.6%	4.3%	-0.6%	4.3%	0.9%
2002-03	-0.9%	0.8%	-0.9%	0.8%	6.7%
2003-04	-0.6%	-2.5%	-0.6%	-2.5%	-2.5%
2004-05	-0.2%	0.4%	-0.2%	0.4%	0.0%
2005-06	-0.5%	-0.1%	-0.5%	-0.1%	-0.2%
2006-07	-0.6%	-0.6%	-0.6%	-0.6%	-7.9%
2007-08	-1.3%	-0.3%	-1.3%	-0.3%	0.3%
2008-09	-0.1%	0.1%	-0.1%	0.1%	-0.1%

Factors compared:	5/3		5/4		
Effect	Activity	Structure	Activity	Structure	Intensity
2009-10	-0.3%	-0.3%	-0.3%	-0.3%	2.3%
2010-11	-0.2%	0.0%	-0.2%	0.0%	1.3%
2011-12	-0.2%	-0.6%	-0.2%	-0.6%	1.9%
2012-13	-0.2%	0.2%	-0.2%	0.2%	-0.6%
2013-14	-0.2%	0.2%	-0.2%	0.2%	1.7%
2014-15	0.0%	0.0%	0.0%	0.0%	0.0%
2015-16	-0.2%	2.6%	-0.2%	2.6%	-18.4%
Mean of absolute values	0.4%	0.8%	0.4%	0.8%	2.4%
Min	-1.3%	-3.1%	-1.3%	-3.1%	-18.4%
Max	0.0%	4.3%	0.0%	4.3%	6.7%

2.5.2.2. *Sensitivity analysis of LMDI decomposition with respect to sectoral aggregation*

The availability of data can often affect the number of sectors included in the decomposition, either in the sense that only some sectors are included or that the sectors are aggregated to some degree. Although, as Rørmose & Olsen (2003) and (Seibe, 2003) find, the more aggregated input data for the decomposition analysis is, the more information is lost. We focus on the role of sectoral aggregation of results of LMDI decomposition here.

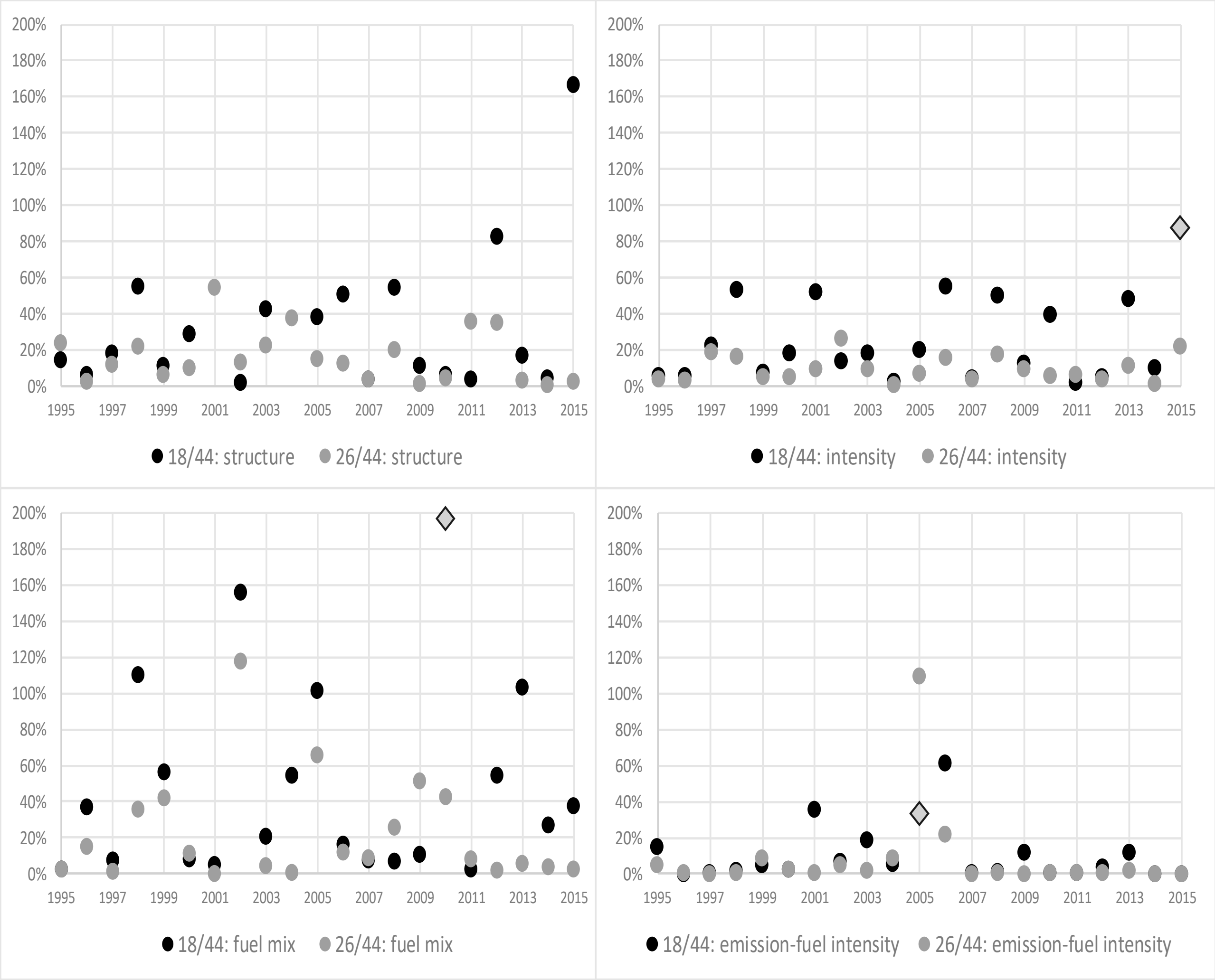
Since we need to have consistent dataset at least from 1995, we aggregate the economic sectors to 44 and to 26 sectors, in order to have a consistent dataset from 1990 to 2016. We created a third aggregation of 18 sectors to test the impact of aggregation on values of factors in LMDI decomposition. The 44 sector aggregation is our reference as the most detailed LMDI decomposition we are able to perform with a consistent dataset.

Figure 17 depicts the relative difference in the values of intensity, structure, fuel mix and emission effects with respect to the values of effects based on LMDI with 44 sector aggregation. The differences in activity effects across the three sectoral aggregation are negligible (up to 0.9 %), as shown in Table 3. The bias from the 44 sector aggregation is significantly lower in the case of 26 sectors than in the case of just 18.

On average, the structure, intensity, fuel mix and emission-fuel intensity effects are biased by 15.7, 9.1, 21.7 and 8.1 percent, respectively, in the 26 sector aggregation from the 44 sector aggregation in the period from 1995 to 2016. The median bias is much lover: 12.3, 6.7, 8.6 and 0.8 percent, respectively. The median of absolute values of effects in LMDI with 44 sectors are 80, 94, 14 and 101 percent for the structure, intensity, fuel mix and emissions factor effects, respectively. We see that the bias is relatively low by the most important effect – the emissions factor effect (0.8 % on median).

Figure 17 Relative difference in effect value using LMDI with 18 and 26 sectors relative to the effect value based on LMDI with 44 sectors

Note: Absolute value of percentage difference relative to the factor value derived from the LMDI with 44 economic sectors.



There are three cases with very large value of difference, always when comparing the LMDI with 18 sectors and 44 sectors; to display these large values using the same scale we divide the value of percentage difference by ten and display them by rhombus (the large difference are reported for the intensity factor in 2015 [870 %], for the fuel mix factor [1964 %] and for the emission intensity factor [332 %]).

Table 3. Sumary statistics of relative divefences in efect value using LMDI with 18 and 26 sectors relative to the factor value based on LMDI with 44 sectors

		activity	structure	intensity	fuel mix	emission-fuel
min.	18/44	0.0%	1.2%	1.1%	2.0%	0.1%
max.	18/44	0.9%	205.0%	870.6%	1964.2%	331.8%
mean	18/44	0.2%	48.4%	62.2%	132.7%	24.5%
median	18/44	0.2%	17.6%	17.4%	26.5%	3.6%
min.	26/44	0.0%	0.4%	0.0%	0.0%	0.1%
max.	26/44	0.5%	54.1%	26.0%	117.6%	109.8%
mean	26/44	0.1%	15.7%	9.1%	21.7%	8.1%
median	26/44	0.0%	12.3%	6.7%	8.6%	0.8%

2.6. Conclusions

This study applies Logarithmic Mean Divisia Index decomposition to examine the factors that were active in changing the emissions level of four air pollutants from large stationary sources – SO_2, NOx, CO and particulate matters – during the transition and post-transition periods of the Czech economy, from 1990 to 2016. We perform 5-factor LMDI decomposition, in which the standard third factor – emission intensity – is further decomposed to fuel intensity, fuel mix and emission-fuel intensity effects.

Our time span overlaps two versions of the Statistical Classification of Economic Activities in the European Community (NACE) – revision 1 and revision 2. Due to changing NACE nomenclature in the REZZO fuel and emission database and the simplified structure of GVA for the 1990-1994 period, we create two consistent, but aggregated datasets. The first is aggregated to 26 sectors for the entire 1990-2016 period, and the second is aggregated to 44 sectors for 1995-2016.

Following Löfgren & Muller (2010), we consider annual changes rather than decomposition on longer time intervals to avoid biased results. However, we can identify three sub periods in our time span with common trends and similar patterns for SO_2, NOx and particulate matters; 1990-1999, 1999-2007 and 2008-2016. CO emissions developed differently than those of the other pollutants. The largest drop in emissions of all four pollutants occurred in the period from 1990 to 1999, when the emissions decreased cumulatively by at least 74 %. In this period, firms faced a newly competitive environment and new command-and-control regulations. As a result, a negative fuel emissions factor effect was the key driver of emissions reductions. However, the fuel intensity effect contributed most to reduction of SO_2, NOx and PM emissions in the first 3 years after the Velvet Revolution, when the Czech and Slovak economies uncoupled. In 1999, all large stationary emission sources were required to comply with emission limits introduced in 1991. Therefore, it was mainly market mechanisms that affected development of SO_2, NOx and PM emissions. Economic growth reflected by a strong positive activity effect pushed emissions upwards, though reductions driven by fuel intensity held emissions down. Since 2008, the magnitude of activity, structure, intensity and emissions factor effects moved closer. In the last two years of our time span, 2015 and 2016, the emissions factor effect became important again, as large stationary emission sources were required to comply with strict new emissions limits based on the directive on industrial emissions. The fuel mix effect reaches absolute values higher than 6 % only in relation to CO emissions (up to 15 % in 2005-2006 and 2006-2007).

To identify differences in 3-, 4- and 5-factor LMDI decomposition, we perform a sensitivity analysis for SO2 emissions with our most detailed dataset of 44 sectors during 1995-2016. The differences in the emission intensity in 3-factor LMDI and emission coefficient effects related to total energy consumption in 4-factor LMDI, which are decomposed into more detailed effects by 4- and 5- factor LMDI, are as expected. We want to highlight that adding a fuel specific dimension – in the 5-factor decomposition –affects not only the last factor that is decomposed, but decreases all other LMDI effects in most cases. In our case, the activity effect is reduced by up to 1.3 %, the structure effect by up to 3.1 % and the fuel intensity in the 4-factor decomposition is reduced by up to 18.4 %. Nevertheless, the means of absolute values of the differences are significantly lower: 0.4, 0.8 and 2.4 percent for the activity, structure and fuel intensify effect, respectively.

Since we have two datasets with different sector breakdowns of the economy, we perform a sensitivity analysis of 5-factor LMDI decomposition of SO2 emission with respect to levels of sector breakdown. We also add a third sectoral breakdown of 18 sectors to our two datasets with 44 and 26 sectors. We summarise our result so that, the more aggregated the economic sectors are, the larger the bias is. The differences breakdowns for 44 sectors are at least 3 times lower with 26 sectors than with 18. The differences in the activity effects are negligible. On the other hand, we find the highest relative differences driven by the fuel mix effect, which may be related to the low magnitude of this effect. The relative differences in absolute values of LMDI effects between the breakdown to 44 and 26 sectors, which we use for our decomposition from 1990 to 2016, are on average 0.1, 15.7, 9.1, 21.7 and 8.1 percent for the activity, structure, intensity, fuel mix and emission-fuel intensity effects, respectively. Our results support applying as detailed a sector disaggregation as possible in decomposition analysis. Therefore, we provide complete results of LMDI decomposition for 26 sectors across 1990-2016 in the main body of the paper and for 44 sectors in periods of 1995-2016 in the Appendix A.

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3. Impacts of Reclassified Brown Coal Reserves on the Energy System and Deep Decarbonisation Target in the Czech Republic[1]

Abstract: In 2015, a 24-year-long prohibition of coal mining within some territories in the North Bohemia coal basin was lifted and as a consequence mining a part of the brown coal reserves might well be resumed. This paper analyses the impacts of maintaining the ban versus three options for a less environmentally stringent policy on the Czech energy system; fuel- and technology-mix, the costs of generating energy, emissions and related external costs up to 2050. We find that overall the effect of lifting the ban, on coal usage, air pollutant emissions and hence externalities is rather small, up to 1–2% compared to the level of keeping the ban. The small difference in the impacts remains even if changes in the prices of fossil fuels and European Emission Allowances or different development in nuclear power usage are assumed. In fact, changing these assumptions will result in more pronounced differences in the impacts than the four policy options might deliver. Maintaining the ban would not achieve the European Energy Roadmap 2050 target and the newly adopted policy and the other two counter-environmental proposals would miss the 80% reduction target to an even greater degree. The environmental and external health costs attributable to emissions of local air pollutants stemming from power generation are in a range of €26–32 billion over the whole period and decline from about 0.5% of gross domestic product in 2015 to 0.1% in 2050.

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3.1. Introduction

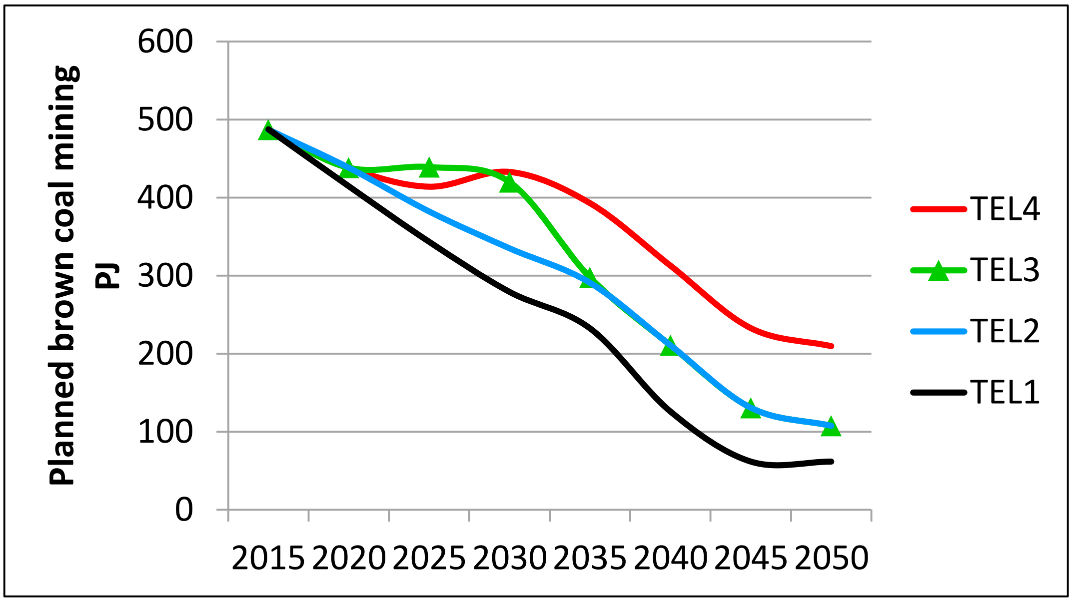
In response to the massive destruction of the landscape and air pollution resulting from brown coal mining in North Bohemia and its combustion in nearby power plants (Glassheim, 2006), in 1991 the Czech government decided to restrict brown coal mining to specified ‘Territorial Environmental Limits’ (TEL) in the North Bohemia coal basin (the limits define the areas where open-pit mining is allowed and where it is not, and are legally binding according to Decrees No. 331 and 444 on Territorial Environmental Limits on Mining passed in 1991, and further re-confirmed by Decree 1176/2008, by the government of the Czech Republic). Since then, a number of parties have called for the re-opening of the brown coal pits most affected by the restriction – Bílina and ČSA – on the basis of social concerns (to ensure the delivery of cheap coal for central heating), regional employment or energy security (domestic coal supply). Despite this pressure the Czech government re-confirmed the ban in 2008.

A change came in October 2015 when the Czech government lifted the TEL. The government had taken into consideration four variants of retaining or abandoning the TEL. The government did not decide to retain the brown coal mining limits unchanged (TEL1 variant), but in order to ensure a supply of high quality domestic brown coal, particularly to supply Czech heating plants, it revoked its past binding decision and voted in favour of lifting the brown coal mining limits at the Bílina open pit (TEL2). An additional two options concerning the TEL – a partial lifting of the restrictions (TEL3) or even completely abandoning the mining limits regarding the second open pit (ČSA) (TEL4) – remain in the game, as the Czech government has stated that lifting the mining limits at the ČSA pit might be re-considered as part of the next revision(s) of the Czech State Energy Policy (SEP).

The ratified lifting of the brown coal mining limits of the Bílina pit (TEL2) may unfasten approximately 123 Mt (1795 PJ) of newly accessible brown coal over the period 2016–2050. The other two considered TEL variants would constitute a total of 167 Mt (2540 PJ) or even 269 Mt (4280 PJ) of newly accessible brown coal under TEL3 and TEL4, respectively; see Figure 18, more details in Máca & Melichar, (2016). The use of newly accessible brown coal reserves may result not only in a higher share of brown coal in the fossil fuel mix, but it could also have an impact on the deployment of renewable resources and other non-fossil technologies. This would be in sharp contrast with the current EU energy-climate policy, which calls for a reduction in greenhouse gas (GHG) emissions and coal usage, and an increase in the share of renewable energy sources (RES) in final energy consumption (The 20-20-20 target to be achieved at the EU level by 2020 has been updated by setting the EU commitment at 40-27-27 target by 2030 (European Council, 2014), which was integrated into the EU 2050 Roadmap for moving to a competitive low-carbon economy (European

Commission, 2011) which requires reducing greenhouse gases emissions to 80% below the 1990 level by 2050. The 40-27-27 target specifically includes: (1) reduction of the EU's GHG emissions by at least 40% relative to the 1990 level; (2) an increase in the share of renewables to at least 27% of the EU's final energy consumption; and (3) an increase in energy efficiency by at least 27%. These new 2030 EU targets will be accompanied by the reform of the EU Emission Trading System and by a package of measures to achieve a competitive, affordable, secure, and sustainable energy supply for the EU (European Commission, 2014). It is worth noting that hand-in-hand with the discussion on the Territorial Ecological Limits on brown coal mining, the political debate over the building of new nuclear reactors in the Czech Republic has been revived. The new SEP (MPO, 2015b) adopted in 2015 assumes that one or two new nuclear reactors might be built around 2035, although a public tender on building two new nuclear reactors was cancelled in 2014 due to the unwillingness of the government to guarantee a contract for a difference in power price.

Figure 18 Planned brown coal mining in the four Territorial Environmental Limits variants (5-year averages).



Source: own compilation based on Ščasný, Máca, Melichar, & Rečka, (2015)

Our paper contributes to energy system modelling in a threefold manner. First, while most modelling work has targeted policies aimed at improving welfare (that will reduce energy use or emissions), our study presents the opposite case. We model the impacts of re-opening brown coal mines that differ in the scope of lifting the territorial ecological limits for mining. We specifically assess the impacts of brown coal availability on the Czech energy system and on the possibilities of achieving carbon reduction and renewable energy targets. More generally, we examine whether new domestic brown coal reserves will be needed to satisfy the predicted domestic demand on energy services. Second, we perform a sensitivity analysis based on several assumptions concerning fossil fuel prices, the European Emission Allowances (EUA) price, and nuclear power usage. Specifically, we assume three sets of the baseline scenario that only differ in the usage of nuclear power, while the remaining six scenarios assume a higher or lower fuel and EUA prices with various combinations of nuclear power. We find that it is the lower price of EUA and/or higher price of fuels – rather than the expansion of brown coal mining – that differentiates the impacts. Third, in addition to the impacts on the energy system we also quantify the impacts in terms of policy indicators – the share of RES technologies in the energy mix, to what degree each scenario and policy will miss the 2030 or the 2050 carbon emission reduction targets, and what the environmental damage and health external costs will be. We find that the damage might be around 1% of GDP over the whole analysed period and thanks to the new policy that expands brown coal mining, no policy targets will be reached.

The previous analyses of the impact of brown coal availability on the Czech energy either address two policy options only (Rečka & Ščasný, 2016) or assume one set of EUA and fossil fuels prices only (Rečka & Ščasný, 2018). Máca & Melichar (2016) quantified the health effects of airborne emissions from coal mining and the use of extracted coal in all TEL variants, as assumed by the Czech government, but they did not analyse the impacts on the energy system and hence emissions attributable to optimized energy mix. This paper applies a new extended Integrated Markal Efom System of the Czech Republic (TIMES-CZ) covering the whole energy sector to assess the impacts of all four policy options in question. Moreover, this paper enhances the previous analyses by performing sensitivity analyses built on various assumptions of fuel costs and the CO_2 allowance price, including three possible pathways of nuclear energy in the Czech Republic. Specifically, we are interested in whether the impacts of the newly adopted policy and the other two counter-environmental policy proposals will be weakened or strengthened if different fuel and EUA prices or different development in nuclear power usage are assumed.

Our results show the ratified lifting of the Territorial Environmental Limits – as agreed in 2015 (TEL2) – may induce a higher use of brown coal between 400 PJ and 1317 PJ in the Czech energy system over the period 2015–2050 when this range depends on future fuel and EUA prices and/or nuclear power deployment after 2035. It would imply 37–99 Mt GHGs of released emissions compared to the TEL remained unchanged (TEL1). However, the impacts of an additional revocation of Territorial Environmental Limits under variants TEL3 and TEL4 are very small, since the additional available brown coal reserves exceed domestic demand for brown coal. The 2030 carbon targets will be achieved under all three policy variants that may revoke the coal mining restrictions. According to our assumptions, this target will of course also be achieved by the more stringent policy, TEL1. However, not even the TEL1 restrictive policy variant would achieve the Roadmap 80% target in 2050 and additional measures in both the ETS and non-ETS sectors would be needed to achieve this target. The new coal mining policy as agreed in 2015 and the two alternative options would miss the 80% reduction target by an even larger amount.

In short, the lifting of the brown coal limits as such would not have a significant impact on the deployment of renewable energy sources as they do not compete directly with brown coal but instead compete with more expensive and advanced technologies. Only the use of biomass would be affected, since biomass is co-fired in brown coal power plants. Technology investment costs and fossil fuel prices are in fact the decisive factors for the wider deployment of renewable energy rather than the availability of brown coal. Nevertheless, the share of renewable energy sources per total gross energy consumption may reach 17–24 percent in 2030 and 23–47 percent in 2050. In general, a reduction of nuclear power in the fuel mix will imply a higher share of renewable energy in the energy mix, whereas an increase in the availability of brown coal will lower the share of renewables.

Additional adverse effects of lifting the brown coal limits are the increased environmental and health damages associated with the production of heat and power from coal (Weinzettel, Havránek, & Ščasný, 2012). Our analysis indicates that the newly implemented policy (TEL2) may result in up to €619 million of additional adverse impacts up to 2050; lifting the brown coal limits further would even increase these external costs by further up to €190 million, depending on the modelling assumptions.

The remainder of this paper is organized as follows: the following section provides a literature review of recent research in energy system modelling. Section 3.3 describes the TIMES-CZ model and data sources. Section 3.4 introduces our key modelling assumptions, including assumptions on fuel and EUA prices, costs of new technologies, and the shape of nuclear power development. Section 3.5 summarizes the impacts of the reference policy and three revocation policies for the baseline scenario. A sensitivity analysis of the impacts for each of the four policy variants, assuming various fuel and EUA prices and nuclear power deployment follows. Section 3.6 discusses policy implications and the last section concludes.

3.2. Literature Review

The Integrated Markal Efom System (TIMES) model generator, developed within the “Energy Technology Systems Analysis Program” (ETSAP) of the IEA (see Loulou, Remne, Kanudia, Lehtilä, & Goldstein (2005a, 2005b, 2005c), is a well-established tool for creation of energy models. TIMES has been widely used to assess the decarbonisation pathways and strategies on global (Price & Keppo, 2017), European (Capros et al., 2014), and country level (Amorim et al., 2014; Vaillancourt et al., 2014). Timmerman, Vandevelde, & Van Eetvelde (2014) classify the TIMES model – alongside MARKAL (Loulou, Goldstein, & Noble, 2004), ETEM (Drouet & Thénié, 2009), and OSeMOSYS (Howells et al., 2011) – as an evolved energy system model. The flexibility of TIMES allows it to extend its structure and explore the energy system in more detail as needed.

In the last decade the standard structure of the model has been extended or detailed in several ways. The TIMES model, in the same way as any other similar energy system optimization tool, may be extended beyond the power sector towards to newly added sectors or towards more detail of upstream (fuel) processes. For instance, Zhang, Chen, & Huang, (2016) extend the TIMES model to accommodate the transport sector with biofuel demand, Seixas et al. (2015) add electric vehicles, and Daly et al. (2014) incorporate additionally travel behavior through the cost of time. A model may be then further detailed in several ways. One possible way of extending the model is to descend from national level to *regional model* in order to better reflect regional diversity in the particular energy market, such as better representation of the heating sector that allows making better links to localized heat demand or inclusion of regionally specific biomass supply and hence region-specific costs (Forsell et al., 2013; Vaillancourt et al., 2014). Another stream of the model extension aims at *temporal* and/or *operational* detail of the model. As found, for instance, by Poncelet, Delarue, Six, Duerinck, & D'haeseleer, (2016) in the case of modelling the penetration of intermittent renewable energy sources, improving the temporal representation of their TIMES model may actually outweigh the gains obtained thanks to detailing techno-economic operational constraints. The last possible extension may be based on adding a new impact category, such as GHG and local air pollutants or even adding environmental benefits associated with emissions of these pollutants (Rečka & Ščasný, 2016).

Improving the model detail in any of its parts (with respect to region, time, operation, or technology set) may affect the results and yield considerable uncertainty. (Price & Keppo, 2017) distinguish two sources of uncertainty in the energy models: the one related to model structure and its assumptions, including the level of detail embodied in its structure, as discussed above; and another related to input parameter and data used. They focus on the model structural assumptions and suggest so-called 'modelling to generate alternatives methodology' that allows exploring the near cost optimal solution space by scaling up of the total system cost of the previous standard formulation.

Uncertainty stemming from the latter is most frequently addressed through a sensitivity analysis applied mainly for fuel prices (Seixas et al., 2015), capital costs (Bosetti et al., 2015) or availability of technologies (Fais, Keppo, Zeyringer, Usher, & Daly, 2016), or magnitude of the discount rates (García-Gusano, Espegren, Lind, & Kirkengen, 2016). Nevertheless, the most common approach being followed in the literature (e.g., Forsell et al., 2013; Vaillancourt et al., 2014; Zhang et al., 2016) relies on one set of fuel prices and technology costs that are both exogenous parameters of the model.

This paper extends the TIMES model structure with respect to usage of detailed operational data and linking technology operation to emissions and the damage they cause. It also addresses uncertainty by two means, covering both its sources. First, the simplified structure of the TIMES-PanEu model that is based on aggregated technology data is detailed through the provision of plant level data for the heat and power sector. Second, a sensitivity analysis is performed to investigate the impacts of various assumptions on fuel and EUA price trajectories, including three possible patterns of nuclear energy deployment in the Czech energy system.

3.3. Methods

3.3.1. The TIMES-CZ Model

TIMES-CZ is a technology rich, bottom-up, cost-optimising integrated assessment model built within the generic and flexible TIMES model generator's General Algebraic Modelling System (GAMS) code. TIMES searches for an optimal solution for an overall energy mix that will satisfy pre-defined (exogenous) aggregated energy demand with the least total discounted costs summed over the analysed period.

TIMES-CZ is based on the Czech region of the Pan-European TIMES-PanEu model developed by the Institute of Energy Economics and Rational Energy Use at the University of Stuttgart (Capros et al., 2014) that was originally built on the basis of Eurostat energy balances for 2010. TIMES-CZ is, however, updated to account for 2012 individual- and sector-level data and the base year is calibrated according to the Eurostat energy balance. The TIMES-CZ model covers the entire energy balance of the Czech Republic from primary energy sources to final energy consumption as depicted in Figure B1 in the Appendix B.

Compared to the original TIMES-PanEu model, the structure of the TIMES-CZ is considerably extended through the following three ways. First, all sectors included in the EU Emission Trading System (ETS) are disaggregated up to individual plants (except the iron and steel industry), while the non-ETS part follows the original structure as defined by the

TIMES-PanEu model. Unique multi-fuel mixes are created for the individual ETS sources according their real consumption based on data from EU ETS emission reports. Other input data for individual ETS sources are obtained from the Register of Emission and Air Pollution Sources (REZZO database) regularly compiled by the Czech Hydrometeorological Institute and the energy register maintained by the Energy Regulatory Office. Second, emission trading is adjusted to take into account the transition to auctioning and derogation (The Czech Republic has made use of the derogation under Article 10c of the EU ETS Directive which allows it to give a decreasing number of free allowances to existing power plants for a transitional period until 2019.). Third, district heating demand and supply are both regionalized into 36 regions according to postal codes.

Emissions of greenhouse gases (GHG) attributable to the country-wide energy balance are linked to the TIMES-CZ model. The model includes all GHG emissions stemming from combustion and technological processes, based on emission reports from EU ETS or emission fuel and activity coefficients. GHG emissions from agriculture and Land Use and Land Use Change and Forestry Use (LULUCF) are not included into the model. It is expected that the GHG emission increase from agriculture will be compensated by GHG emission reduction though LULUCF (based on consultations with the Ministry of the Environment of the Czech Republic). This means the GHG emissions in the model equal to the GHG emission balance with LULUCF.

Plant-level emissions of nitrogen oxides (NO_x) sulphur dioxide (SO_2), and particulate matter (PM) stemming from heat and electricity production in the power sector are also included in the model for the reference year. Emission coefficients for later years, as well as emission intensities of new technologies reflect requirements (Best available technologies – BAT) set by the adopted regulation, as well as a new regulation on emission concentration limits for industrial emissions (Directive 2010/75/EU on industrial emissions).

The technical and economic characteristics of new technologies are taken from TIMES-PanEu (Capros et al., 2014). In order to better reflect the newest information on current costs and development of prospective technologies, investment, fixed and variable costs of power generation technologies are updated according to Schröder, Kunz, Meiss, Mendelevitch, & Hirschhausen (2013).

3.3.2. Quantification of Damage

We estimate the impact of energy scenarios on the environment and health that are attributable to air quality pollutants using the ExternE (Externalities of Energy) Impact Pathway Analysis (IPA) (an internet accessible version of EcoSense (EcoSenseWeb1.3) was developed within the NEEDS project (Preiss, Friedrich, & Klotz, 2008). See Máca, Melichar,

& Ščasný, (2012) and Weinzettel et al., (2012) for the details. The IPA is an analytical procedure examining the sequence of processes through which polluting emissions result in damages. The IPA comprises four basic steps: (i) selection of the reference power plant and determination of harmful emissions releases; (ii) calculation of changes in pollutant concentrations for all affected regions using atmospheric dispersion models; (iii) estimation of physical impacts from exposure using concentration-response functions; and (iv) economic valuation of impacts. The IPA covers a range of impacts on human health, buildings and materials, biodiversity, and crop yields (see Ščasný, Massetti, Melichar, & Carrara, (2015) for a detailed description).

In the benefit assessment, we include the most common air pollutants (SO_2, NO_x, PM2.5, PM10) to derive the external cost associated with the releases of these pollutants from district heat and power generation, as endogenously determined by our TIMES-CZ model.

Two approaches may be followed to quantify the external costs over long period in future. First, the same value of damage over the entire period is assumed. Alternatively, the willingness to pay values for avoiding the adverse effects and hence value of damage may be time variant and likely grow over time as real consumption will grow, as assumed, for instance, in Ščasný et al. (2015) (following the approach described in Ščasný et al. (2015) and assuming 3, 2, and 1 per cent growth in real consumption before 2015, during 2015–2030, and after 2030, respectively, we get qualitatively similar results as when no price adjustment is made. In absolute terms, cumulative value of the external costs is about 45% higher with the adjustments. This result is available from the authors on request). In this study we follow the former approach. The magnitude of damage corresponds to the pollutant-specific damage factor that was derived within the EU funded NEEDS project (Preiss et al., 2008).

The ExternE's IPA quantifies the impacts of local air pollutants on human health, biodiversity, crop yield, materials that appear mostly in the EU, and also considers health impacts coming from the Northern hemispheric modelling. The damage factors per ton of pollutant used in this study are as follows: €8371 per ton of SO_2, €9359 per ton of NOx, €25,366 per ton of $PM_{2.5}$, and €1011 per t of PM_{coarse} (all expressed in EUR 2012 using HICP) and these values cover impacts of all the above impact categories. A major part of damage for each of the four pollutant categories is responsible for adverse health impacts, 90% SO_2, 79% for NOx, 99% for $PM_{2.5}$ and PM_{coarse}. Impacts on biodiversity contribute by 5%, 15%, for SO_2 and NOx, respectively, and materials effects comprise 6%, 1%, for SO_2 and NOx, respectively.

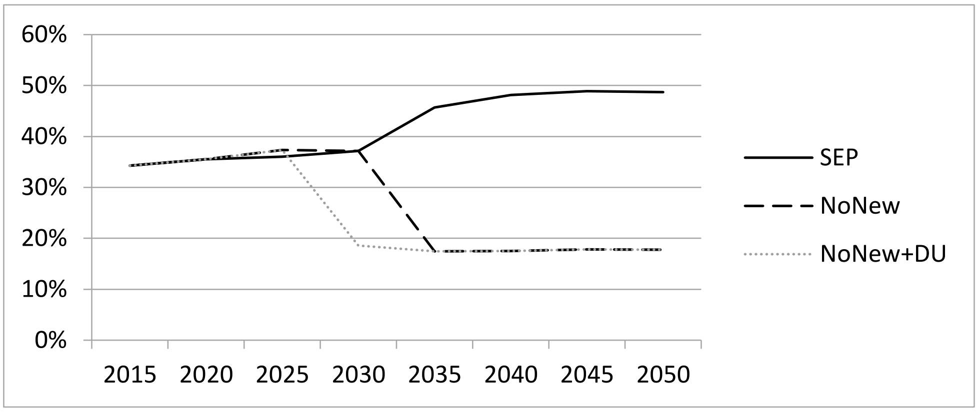
3.4. Scenarios and Assumptions

The impacts on the energy system and costs are analysed for all three policy variants for lifting the Territorial Environmental Limits. TEL2 is currently a binding policy that revoked the past binding decision about the Territorial Environmental Limits on brown coal mining and allowed the revocation of the brown coal mining limits in one of the two regulated open pits (Bílina). In 2015, The Czech government also considered partially (TEL3) or even completely (TEL4) lifting the mining limits in the second open pit (ČSA). Although the last two policy variants have not been implemented – as stated by the Czech government – lifting the mining limits at the second pit might be re-considered in the next revision(s) of the State Energy Policy. The impacts of three revocation policies (TEL2, TEL3 and TEL4) are compared to the effects of a reference policy variant (TEL1) that assumes the Territorial Environmental Limits in the two open pits, as agreed in 1991 and revoked in 2015, would be untouched.

Further, we perform a sensitivity analysis to investigate the impacts of various assumptions on fuel and EUA price trajectories and for three possible patterns of nuclear energy deployment on the energy system, emissions, cost and benefits.

Considering the actual costs and power market situation, any decision on building new nuclear reactors is conditional on public support and hence policy decisions. In fact, as revealed in our previous modelling (Rečka & Ščasný, 2013, 2016), no nuclear power plant would be built within the Czech energy system as a result of a free market decision. Despite this fact, the new State Energy Policy (MPO, 2015b) assumes one or two nuclear reactors will be built around the year 2035. Our modelling therefore assumes three possible pathways in developing new nuclear power plants within the Czech energy mix, as depicted in Figure 19. The first pathway (‘SEP’) reflects the 2015 State Energy Policy when new nuclear blocks are constructed around the year 2035, the operational nuclear power plant in Temelín will operate at least until 2050, and the second nuclear power plant in Dukovany may operate until 2035.

Figure 19 Three assumptions on development pathways for nuclear energy, share of electricity production



The next two nuclear energy pathways assume no new nuclear power plant construction. While "NoNew" assumes the same operation lifetime for the two current operating nuclear power plants as in "SEP", "NoNew+DU" assumes that the second nuclear power plant in Dukovany will be phased out earlier while the current operation permits are still valid (two out of four blocks at the Dukovany power plant are permitted to operate till 2025, the other two blocks may obtain operational permission till 2027 in 2017. The extension of operations till 2035 and 2037 should be technologically possible, but may not be politically acceptable due to political pressures from the EU (and Austria especially), calling for the shut-down of the Dukovany power plant before 2027.

We note that the share of nuclear power in electricity generation, as described in Figure 19, is given by the three assumptions on nuclear power deployment and is hence exogenous in the TIMES-CZ model. It implies that other technologies are chosen on the basis of cost optimisation to complete (exogenous) aggregate electricity demand and generate all (exogenously given) heat.

The following three different assumptions on fuel prices are considered (see Table 4). The first and the last fuel price sets are based on the World Energy Outlook (IEA, 2014). While the first one represents WEO *450 Scenario* that may achieve the 450 ppm carbon concentration target, the last one follows WEO *Current Policies Scenario.* The second (Middle) price set is defined as the average of more than ten price scenarios taken from several studies, including (European Climate Foundation, 2010; Gavor, 2013; IEA, 2014; Schröder, Kunz, et al., 2013; Schröder, Traber, & Kemfert, 2013). The highest fuel prices are assumed in WEO-CP. Achieving the 450 ppm target will drastically lower demand for fossil fuels which consequently implies the lowest prices for fossil fuels. The price of other fuels, including biomass, biofuels and nuclear fuel, are assumed to be the same across all assumption sets.

Table 4. Commodity only prices as assumed in the TIMES-CZ model (€/GJ).

Assumption	Fuel	2015	2020	2025	2030	2035	2040	2045	2050
WEO-450	Hard coal	2.3	2.4	2.2	2.1	2.1	2.1	2.0	2.0
	Natural gas	7.9	7.8	7.6	7.4	7.1	6.8	6.5	6.3
	Oil	13.0	12.9	12.7	12.5	12.4	12.3	12.1	12.0
	Brown coal – Czech	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
	Brown coal – import	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Middle	Hard coal	2.6	2.9	3.0	3.1	3.2	3.3	3.4	3.5
	Natural gas	8.2	8.5	8.3	7.8	7.6	7.3	7.8	8.4
	Oil	13.0	12.9	12.7	12.5	12.4	12.3	12.1	12.0
	Brown coal – Czech	1.6	1.6	1.6	1.7	1.7	1.7	1.8	1.8
	Brown coal – import	1.8	1.8	1.8	1.9	1.9	1.9	2.0	2.0
WEO-CP	Hard coal	2.3	2.9	3.0	3.1	3.2	3.3	3.4	3.5
	Natural gas	8.2	8.5	9.2	9.8	10.1	10.4	11.2	12.0
	Oil	13.0	13.7	14.4	15.1	15.6	16.2	16.8	17.4
	Brown coal – Czech	1.6	1.6	1.6	1.7	1.7	1.7	1.8	1.8
	Brown coal – import	1.8	1.8	1.8	1.9	1.9	1.9	2.0	2.0

Four different patterns of the future market price of GHG emissions allowances (EUA) are assumed, as depicted in Table 5. Both the SEP and WEO Current Policy Scenario assume EUA at about €40 in 2050, with different paths for reaching this level. The highest EUA price is determined by achieving the 450 target. The lowest EUA price is assumed to reach about €28 in 2050 only and reflects the potential failure of the structural reform of the EU ETS.

Table 5. EUA price assumptions (€2012/t CO_2).

EUA price assumptions	2015	2020	2025	2030	2035	2040	2045	2050
SEP	7.5	9.0	23.0	33.0	34.7	36.5	40.0	40.0
WEO-CP	7.5	15.4	19.2	23.1	26.9	30.8	35.2	40.2
WEO-450	7.5	16.9	47.0	77.0	92.4	107.8	125.8	146.7
Low	7.5	8.6	10.4	12.7	17.3	20.7	23.0	27.6

Note: The EUA prices in SEP are in accordance with the Czech SEP (MPO, 2015b). The next two follow EUA prices as predicted by Current Policy or the 450 ppm scenario in WEO (IEA, 2014). The last EUA price pattern assumes the structural reforms of the EU ETS (European Parliament & Council of the European Union, 2015) will fail and the EUA price would increase gradually up to €27.6 in 2050 only.

Combinations of nuclear energy pathways, fuel price sets and EUA prices define our assumption sets to be used in the sensitivity analysis. For the sake of clarity, however, for each of the four policy variants (TEL1–TEL4) we analyse only nine out of all 36 possible assumption sets considered, as depicted in Table 6.

Table 6. Assumption sets for each of the TEL variants.

Parameter	Assumption Set	BL	BL-N	BL-N+D	CP	CP-N	CP-N+D	EUAlow-Faver	EUAlow-Fhigh	450 ppm
Fossil fuel price	WEO-450 (low)									x
	Middle	x	x	x				x		
	WEO-CP (high)				x	x	x		x	
EUA price	SEP	x	x	x						
	WEO-Cur-pol				x	x	x			
	WEO-450									x
	Low							x	x	
Nuclear power	SEP	x			x			x	x	x
	NoNew		x			x				
	NoNew+DU			x			x			

The baseline assumption set (BL) is in accordance with the 2015 SEP; it assumes the Middle fuel prices of the middle high EUA price trajectory (SEP), reaching €40 in 2050, and the building of two new nuclear reactors. Impacts for all remaining scenarios are evaluated relative to the impacts of the respective policy variant with the baseline assumption set.

Half of the remaining assumption sets assume new installations of nuclear power plants according to the 2015 SEP, while no new nuclear reactor will be built in the last four assumption sets.

Two out of the remaining eight assumption sets are the same as the BL, although in contrast to the BL, no nuclear power plant will be built (BL-N) and the Dukovany nuclear power plant will be decommissioned in 2027 (BL-N+D) already. The next three sets (CP, CP-N, and CP-N+D) have the same scenarios as (BL, BL-N, and BL-N+D), but the fuel price set follows the WEO's Current Policy Scenario rather than the Middle fuel price set.

The next two assumption sets represent a very conservative scenario as both assume a low EUA price, always below €28 per ton of CO^2, new nuclear plants, and Middle fuel prices (EUAlow-Faver), or high fuel prices (EUAlow-Fhigh), respectively.

The 450 ppm assumption set is the only one that addresses the 450 ppm target. We note that while the (market) prices of fossil fuels are the smallest in this scenario, the expected (regulated) price of EUA is the highest among all four assumption sets. This set also assumes new nuclear plants will be installed.

Overall, combinations of four TEL variants and nine assumption sets define our 36 scenarios (named by variant and assumption set, i.e., TEL1 CP) for which the impacts are quantified.

Aggregate electricity production and heat consumption are exogenous in accordance with the 2015 SEP and the same in all scenarios. Namely the gross electricity production decreases slightly from 92 TWh in 2015 to 89 TWh in 2050 (domestic consumption increase but net exports drop from 21 TWh in 2015 to 2.5 TWh in 2050). Since we are interested in the net effect of various brown coal availability scenarios, no public support provided for renewable energy or for other alternative or efficient energy technologies is considered in any of the presented scenarios.

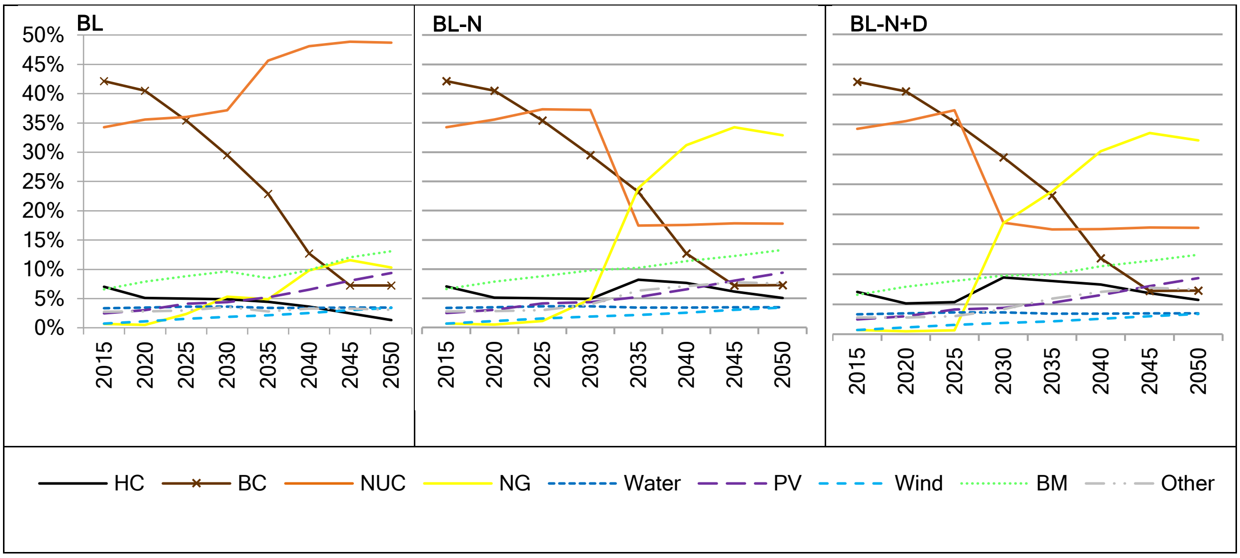
3.5. Results

3.5.1. Baseline Assumption Set

The baseline assumption set (BL) is in line with the Czech State Energy Policy agreed in May 2015. A new nuclear power plant is built around the year 2035. Its new capacity exceeds the capacity of the Dukovany nuclear power plant which is due to expire. As a result, the share of nuclear energy in electricity production increases from 34% in 2015 to 37% in 2030 and to 45% in 2045–2050. This trend holds for all four TEL policy variants for the BL assumption set.

Usage of brown coal to generate electricity and heat is limited by brown coal availability in TEL1 that keeps the ban on brown coal reserves. Consequently, the share of brown coal in power generation will decrease by 80% from 42% in 2015 to 7% in 2050. Brown coal is replaced by an increase in nuclear power generation and natural gas in particular, followed by greater use of all renewable energy (biomass and bio gas, photovoltaics, with a minor increase in wind energy). This trend is displayed in Figure 20.

Figure 20 Fuel shares in power generation in the TEL1 variant for the three baseline assumption sets defined by a decision on a new nuclear power plant



Note: HC – hard coal, BC – brown coal, NUC – nuclear, NG – natural gas, PV – photovoltaics, BM – biomass & biogas.

Whether a new nuclear power plant will be built or not considerably affects the future fuel mix for power generation. Figure 20 compares the fuel shares for TEL1 with new nuclear power (BL, left panel), with no new nuclear power plant and the Dukovany nuclear plant phasing out around 2035 (BL-N, middle panel), or with faster expiration of Dukovany in 2025 (BL-N+D, right panel).

Without new nuclear reactors, nuclear power will fall to 18% (as exogenously given) when natural gas will mainly compensate for this decline (with 34% of power generation), followed by more extensive hard coal usage in existing technologies. Without additional policy measures, nuclear energy will be predominantly substituted by fossil technologies – natural gas and hard coal mainly. The price ratio between natural gas and hard coal plays a decisive role whether natural gas or hard coal power plants will be installed. Specifically, if the price of natural gas increases to 12 €/GJ and the price of hard coal only increases to 3.5 €/GJ, then natural gas technologies will no longer be able to compete with hard coal and no new natural gas power plants will be built. This is the result we observe in CP, EUAlow-Fhigh, CP-N and CP-N+D scenarios (see Figure 24).

A decision on building a new nuclear power plant will have no considerably large effect on renewable energy. In fact, the share of biomass will remain the same across all three baseline assumption sets for TEL1, reaching 10% in 2030 and 13% in 2050. The share of renewable energy sources for power generation will also be same, amounting to 20% in 2030 and 29% in 2050. Due to the relatively high total costs of electricity from renewable energy sources[2] and the lack of public support assumed in this study, brown coal availability does not affect the share of wind and solar energy – this result is robust as it holds for all three baseline sets and across all four policy scenarios (TEL1–4), (see Figure 24 or Figure S2 in Supplementary Materials).

As a consequence of declining coal usage, total Czech GHGs emissions would decline in TEL1 by almost 50% from 108 Mt in 2015 to 56.5 Mt in 2050. If no nuclear power plant is built (TEL1 BL-N), total GHG emissions would be 10% larger by about 5.6 Mt in 2050, corresponding to about 3% of the 1990 benchmark level (see Figure 29). The effect of the phasing out of the Dukovany nuclear power plant earlier would increase GHG emissions by an additional 4.3 Mt of GHG a year, but only in a 5-year span around 2030 (compared to BL-N). The 2050 carbon target will be missed in any case, reducing GHG emissions by 68–71% in 2050.

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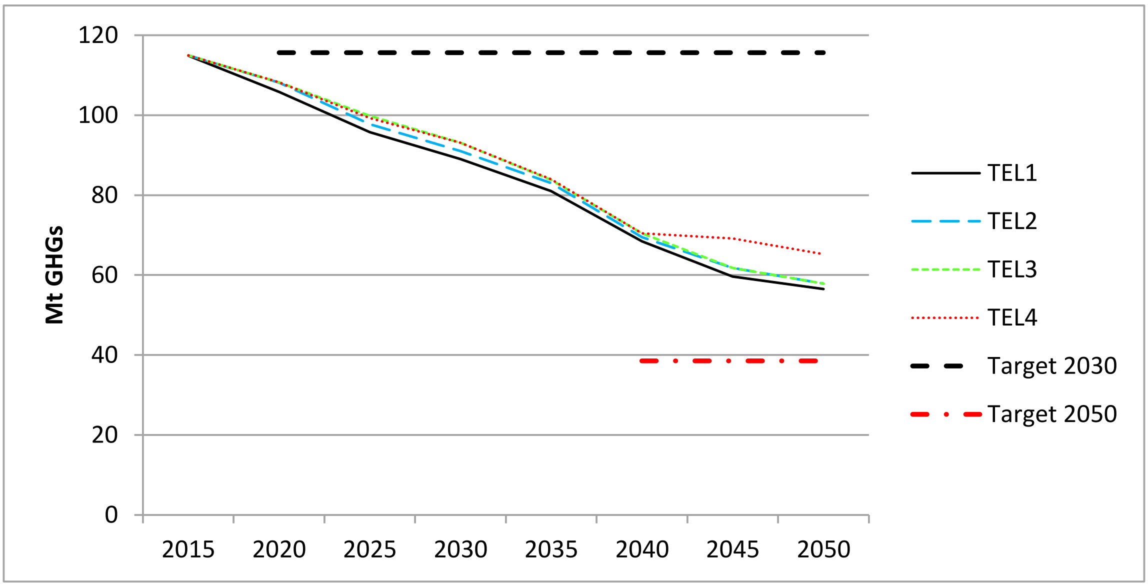
[2] Wind and PV power plant have low utilization of installed power resulting in high total cost of electricy.

Total annualized costs of the whole energy system across all industries will double from €26bn in 2015 to €52bn in 2050. Investments are the main driver of this cost increase. This is partly due to the fact that the current level of investment in the energy sector is very low while the technology portfolio to generate electricity and heat is getting older, partly due to capital-intensive new technologies (the model assumes complete replacement of transport fleet by 2025). Fixed operational & maintenance costs will increase over time as well, but at a much lower pace, by 20% from €2bn in 2015 to €2.4bn in 2050, and variable costs will range between €2.4bn and €2.9bn. On the other hand, fuel cost will decline from €11bn to €8.5bn in 2050 as a result of the increasing share of renewable energy and lower primary energy consumption. Costs for purchasing the EUA will only represent a small share – €0.5bn in 2015–2020 – and then will rise to €1.5bn in 2030 and decline to €0.8bn in 2050 despite the increase in the EUA price.

Partial revocation of the coal limits (TEL2, TEL3) only slightly increases GHG emissions compared with TEL1 BL scenario, mainly between the years 2020 and 2035. Lifting the limits completely (TEL4) increases GHG emissions from 2040 by about 10 Mt each year (this is the equivalent of about 5% of the 1990 level) (see Figure 21). This can be translated as a 66 to 70% GHG emission reduction in 2050.

Figure 21 GHG emissions in assumption set BL until 2050 in all 4 TEL variants



3.5.2. Sensitivity Analysis

The sensitivity analysis evaluates the variance in the impacts on the Czech energy system for four variants of TEL policies, assuming various fuel and EUA prices.

3.5.2.1. Brown Coal

Total consumption of brown coal in all Czech sectors declines in all scenarios between 2015 and 2050, see Figure 22. The ban on brown coal mining in TEL1 effectively restricts brown coal consumption. Over time, brown coal use will decrease from 501 PJ in 2015 to 90–93 PJ in 2050, with the lowest volume under the 450 ppm assumption set. The TEL1 variant will also yield the lowest cumulative aggregate brown coal consumption over 2015–2050, which is around 10,000 PJ for all nine assumption sets. The adopted policy (TEL2) will result in slightly larger cumulative brown coal use, with the highest volume around 11,317 PJ under the EUAlow-Fhigh assumption set that is still 478 PJ below the economically and technically available reserves to be mined in TEL2.

At the beginning of the analysed period (2015–2020), lifting the limits will increase brown coal consumption by only about 23 PJ per annum (by 5%) in all three TEL2–4 variants under all assumption sets (and domestic brown coal will replace imported brown coal). After 2020, however, fuel and EUA prices and whether new nuclear power will be used or not will start to affect brown coal consumption in TEL2–4 more than the availability of brown coal. This can be seen in Figure 22, which shows a minimal difference in brown coal consumption among the three TEL2–4 variants for 450 ppm or BL-N assumption sets during the whole period. From 2040 onwards, the high price of EUA and the relatively low price of natural gas may lead to the same or even a slightly lower volume of brown coal usage in TEL2-4 than in TEL1 with the ban This is a consequence of the need to install new capacities in TEL1 sooner than in TEL2–TEL4, where it is optimal to install more advanced technologies later.

Additional lifting of the limits above the present status in TEL3 and TEL4 increases the brown coal usage only, compared to TEL2, when a low EUA price or a high price of natural gas are assumed (EUAlow-Faver, EUAlow-Fhigh or BL, BL-N+D, CP, CP-N, CP-N+D). TEL3 makes available the highest volume of brown coal among all TEL variants during 2025-2035. In this period, TEL3 with high prices of natural gas and hard coal, or a low price of EUA (CP, CP-N, CP-N+D or EUAlow-Fhigh) would lead to the highest brown coal usage. At the end of the period, in 20045-50, TEL4 may lead to the highest brown coal mining in BL, BL-N+D and EUAlow-Faver.

When the limits are lifted, the costs of fuel, EUA prices, and development of nuclear energy actually affect brown coal consumption to a greater degree than the availability of brown coal. For instance, under the 450 ppm assumption set, the cumulative consumption of brown coal equates to 10,400 PJ in all three revocation policies (TEL2–TEL4), which is the lowest volume among all assumption sets. This volume is only 400 PJ or 4% larger than the volume involved in the TEL1 prohibition policy. The BL-N assumption set has the same effect on brown coal use in all three TEL2–TEL4 policies, leading to the cumulative consumption of 10,900 PJ. Besides these two assumption sets, the cumulative use of brown coal in TEL2 is always smaller than under the policies that would lift the mining limits in the ČSA pit as well (eitherTEL3, or TEL4 or both). The high price of natural gas relative to other fossil fuels (CP, EUAlow-Fhigh, CP-N and CP-N+D) and the higher availability of brown coal around 2030 in TEL3 lead to higher cumulative brown coal use in TEL3 compared with TEL2 and even TEL4. In the case of TEL4 when the mining limits will be completely lifted in both mines, we found an additional increase in brown coal consumption compared to TEL2 only in assumption sets BL, BL-N+D and EUAlow-Faver. In these cases, brown coal use will cumulatively reach at least 12,000 PJ, which is at least 20% more than when the limits were in place (TEL1).

3.5.2.2. Power Generation Fuel Mix

In the next step, our sensitivity analysis aims at the fuel mix for power generation in two ways. First, the influence of different EUA and fossil fuels prices as well as different developments of nuclear power are examined on the agreed policy (TEL2). Figure 23 presents the percentage point (pp) differences in power generation fuel mix under specific assumption sets compared to scenario TEL2 BL. Second, all scenarios are analysed together in order to identify the most important drivers influencing the power generation fuel mix (Figure 24).

In analysing TEL2, we find almost insignificant differences in the power generation fuel mix between BL and the 450 ppm scenario. The high price of natural gas relative to other fuels (CP and EUAlow-Fhigh) involves a substitution of natural gas by hard coal (up to 10 pp). A low EUA price (EUAlow-Faver) may lead to higher shares of hard and brown coal (by 4 and 3 pp in 2040 and 2045, respectively) and lower shares of natural gas (up to −4 pp), biomass & biogas and the other resources. The ban on new nuclear reactors makes a significant difference in the power generation structure: hard coal and partly natural gas replace the drop in nuclear energy (CP-N and CP-N+D sets with high price of natural gas); but in BL-N and BL-N+D, replacement of reduced nuclear energy follows the reverse order – natural gas is followed by hard coal and other sources as the price of natural gas is lower than in the previous case.

The first strong finding resulting from the analysis of all scenarios is that the four TEL policy variants affect the fuel mix much less than the assumptions on different fuel prices or the development of nuclear energy. In general, the greater availability of cheap brown coal under

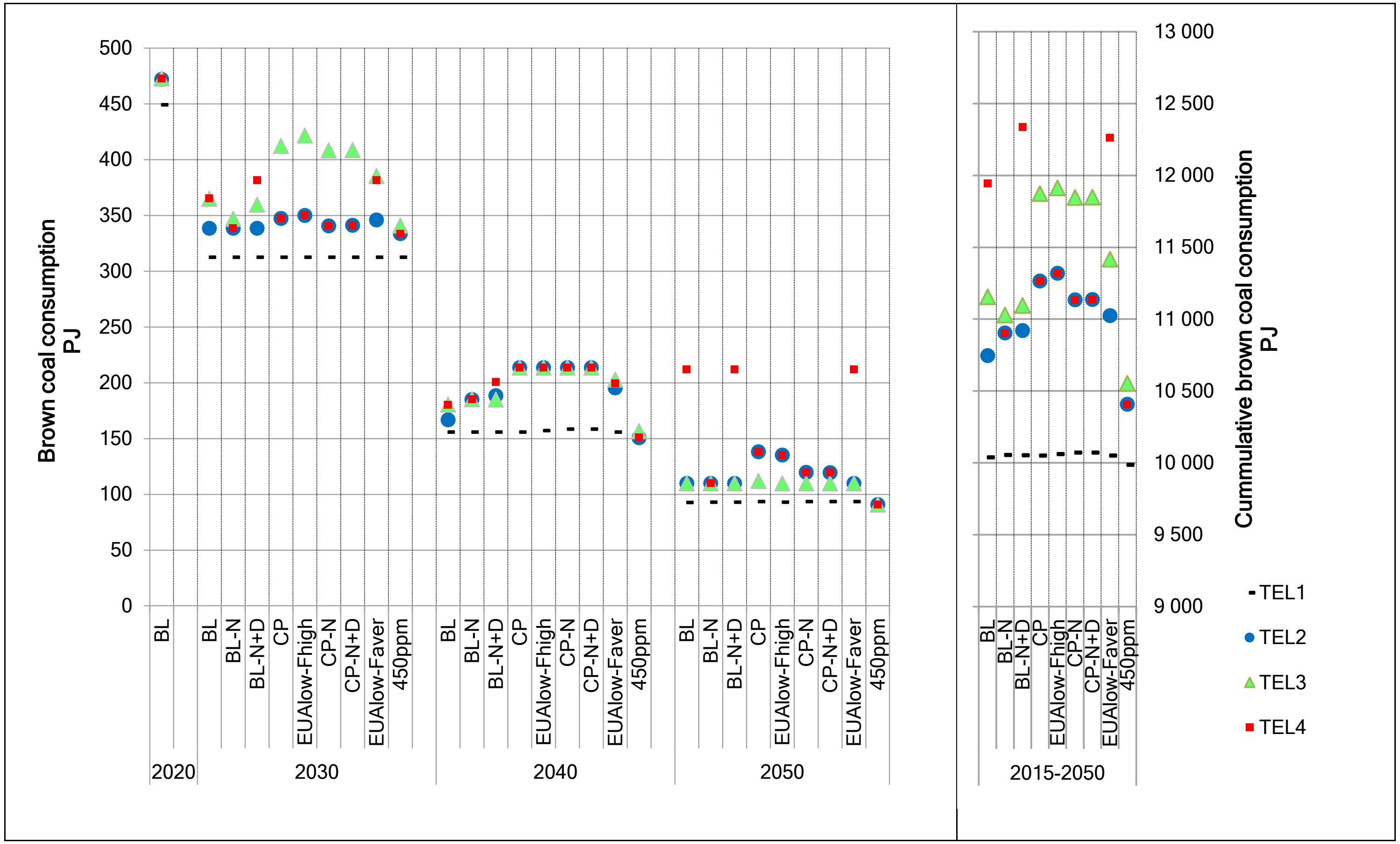
TEL2, TEL3 and TEL4 policies implies that the brown coal substitutes hard coal or natural gas (if the EUA price is low) in the fuel mix.

TEL3 maintains a large number of brown coal power plants still operating up to 2035 and thus results in the highest share of brown coal use for all assumption sets. There is only one case when TEL4 will use more brown coal during 2030–2035 and that is for BL-N+D (see Figure S2 in the Supplementary material).

Figure 24 presents the fuel shares for TEL1, TEL2, and TEL4 under various price assumptions and when the new nuclear blocks will be installed (upper panel) and when these blocks will not be installed (the lower panel).

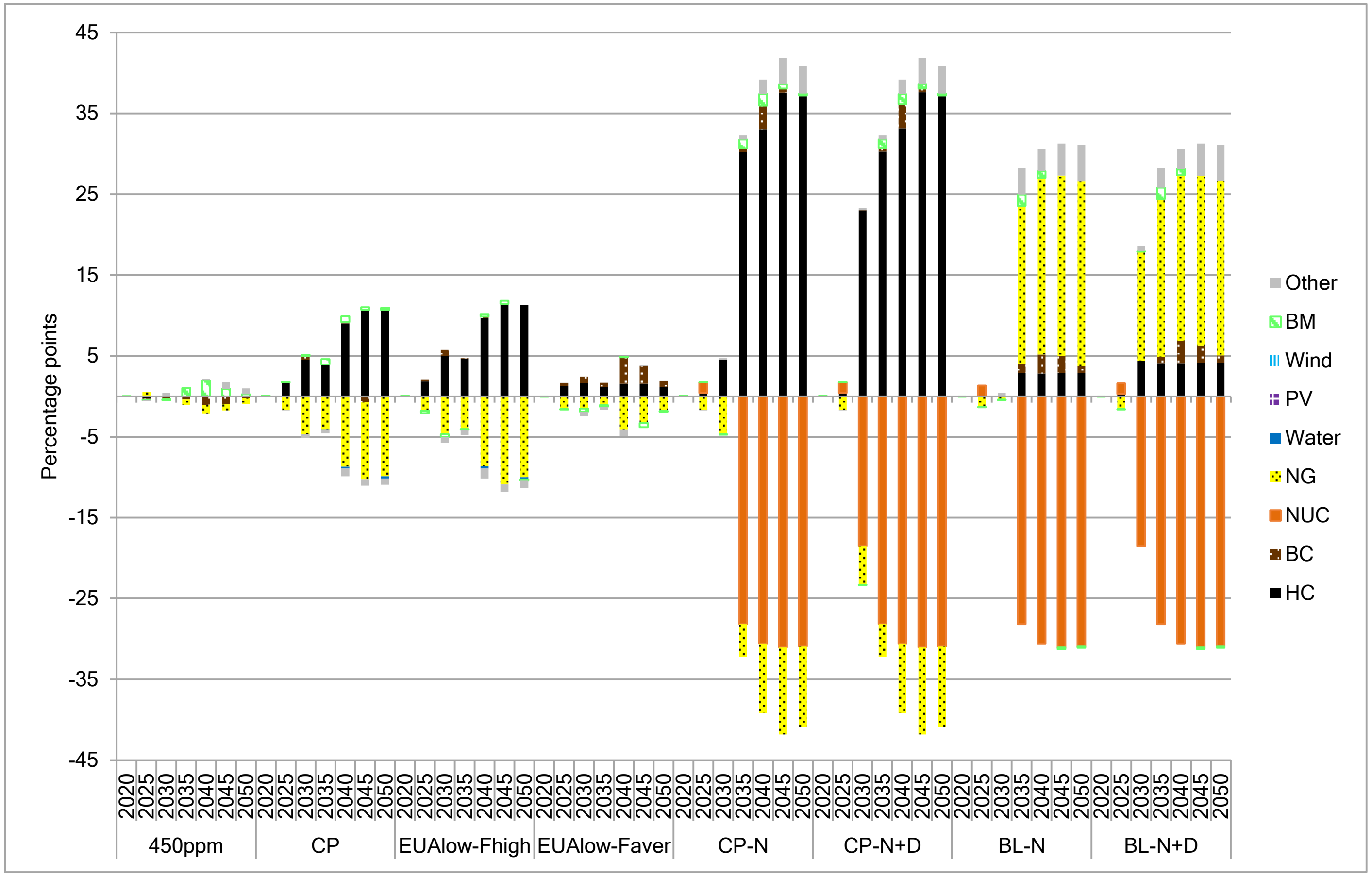
As expected, the future development of nuclear power is the most influential factor for determining what the Czech power system will look like. The policy that lifts the ban and price of EUA and fuels might have a significant impact on the fuel mix only if no new nuclear blocks are be installed. The higher price of natural gas will make natural gas uncompetitive and as a consequence its share will remain very small throughout the entire period and the share of hard coal will increase significantly. The increased availability of brown coal will only be relevant if the price of EUA is be low or if no new nuclear blocks are installed. In other words, a high EUA price will stimulate cleaner sources, such as gas, and new nuclear power will make new supply of domestic brown coal obsolete.

Figure 22 Brown coal consumption in 2020, 2030, 2040, 2050 and cumulatively 2015–2050



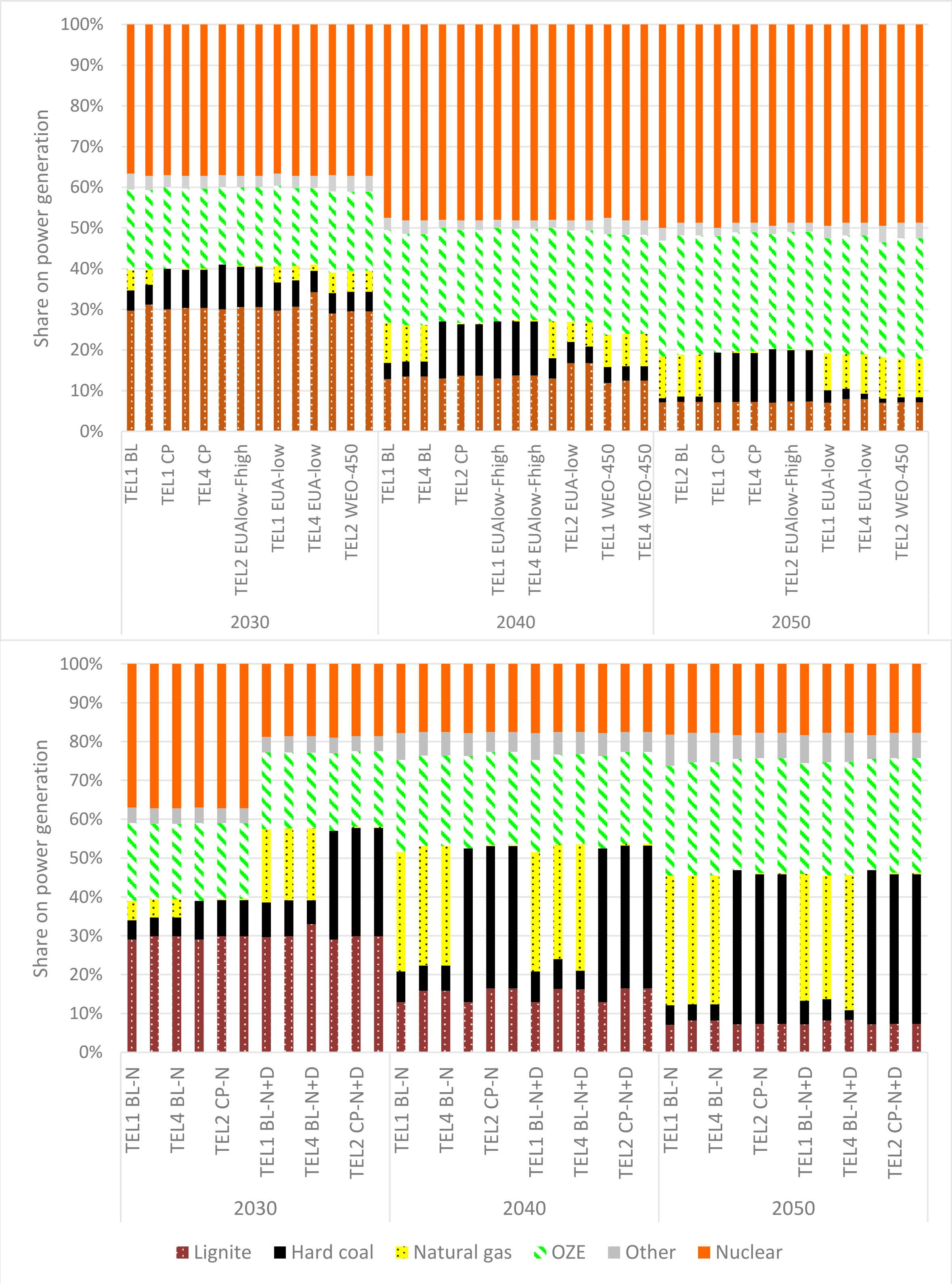
Note: The level of brown coal consumption is the same for all assumption sets in 2020.

Figure 23 Fuel mix for electricity production in TEL2's scenarios compared to TEL2 BL, percentage point difference



Note: HC – hard coal, BC – brown coal, NUC – nuclear, NG – natural gas, BM – biomass and biogas.

Figure 24. Shares of fuels on power generation in selected years and scenarios.



3.5.2.3. *Annualized Costs*

The total costs consist of investment costs, fuel, fixed operational & maintenance, and variable costs, and expenditure on EUA purchases. All costs are annualized taking into consideration the lifetime of each asset, and are expressed in real (not discounted) values[3]. We find that the four policy variants on brown coal mining involve almost same total annualized costs with negligible difference among them, which is up to 0.5% of total costs (in range of −0.03 and 0.27 billion of euro). Different assumption sets involve, however, a larger cost difference as shown in Figure 25 for the TEL2 policy. Compared to the TEL2 BL reference case, the difference in the cumulative sum of total annual annualized costs from 2020 to 2050 resulting from assumption sets covers a range between −27 billion euro and +48 billion euro, when the scenarios without new nuclear reactors (BL-N, BL-N+D) result in the lowest cumulative costs and the 450 ppm set yields the highest sum.

The low price of EUA reduces the total costs by up to €1bn in 2030 (compare EUAlow-Faver and BL). With higher fuel prices (EUAlow-Fhigh), a lower EUA price decreases the payments for emission allowances, but other costs remain unchanged. A very progressive EUA price in the 450 ppm set may increase total costs by €1bn to €2bn between 2025 and 2050, but also lead to savings in fuel costs (compared with the BL set).

The high price of oil may involve a technological shift in the transport sector and as a result this scenario will have the highest impact outside of the EU ETS sectors; it may lead to savings in fuel costs of more than €1bn over 2045-2050 due to partial switch to electrical vehicles, more advanced technologies with higher efficiency, but it may also increase all other costs different than the costs to buy EUA. As a result, the total costs increase by almost €2bn in 2050 under the CP set compared to BL assumptions.

As nuclear technology has the highest investment cost by far, a decision to not build any new nuclear power plants may decrease investment and variable costs in 2035–2050 by €1.4bn and €0.5bn per annum (BL-N and BL-N+D), and the total costs are also lower with no nuclear reactors as a result of lower investment costs for the CP sets (compare CP with CP-N and CP-N+D). Higher fuel and EUA costs may add €0.4bn, or €0.3bn, respectively, to the cost level when low or medium high levels are assumed.

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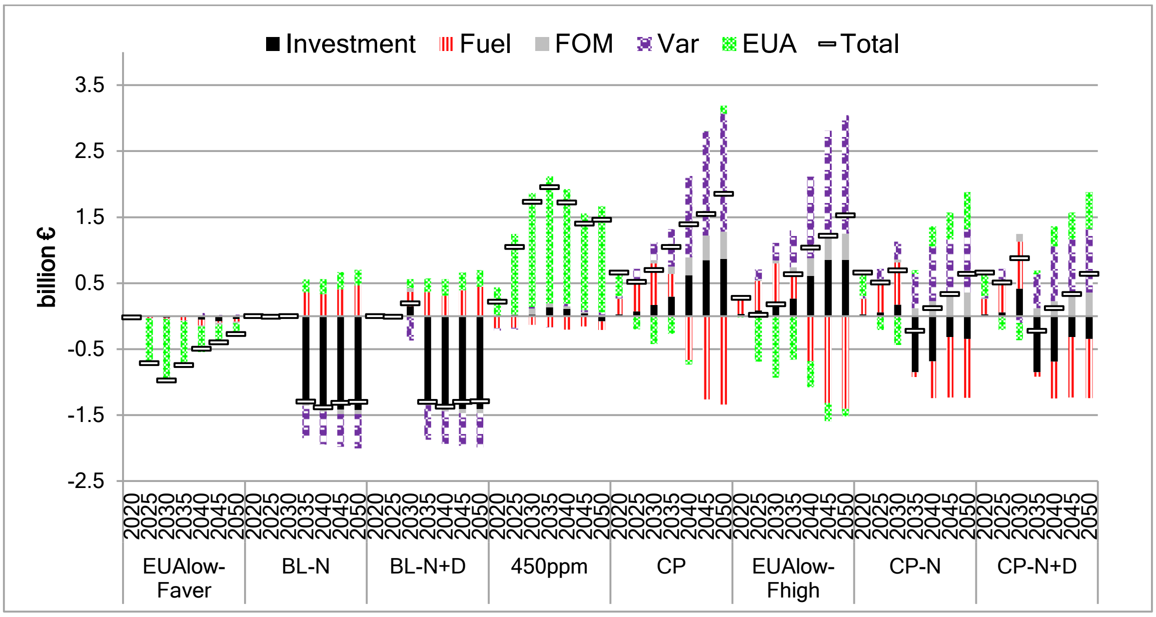
[3] In the case of investment costs, the sum of the annualized payments (made in the beginning of each year within the economic lifetime) are equivalent to a lump-sum investment cost paid at the beginning of the first operation year ($Annualized\ Investmentcost_t = lumpsum\ invesment/lengh\ of economic\ lifetime$). Fuel, fixed operational & maintenance, and variable costs, and expenditure on EUA purchases are annual by default.

Figure 25 Total annualized costs for TEL2 policy, cost difference compared to TEL2 BL reference case

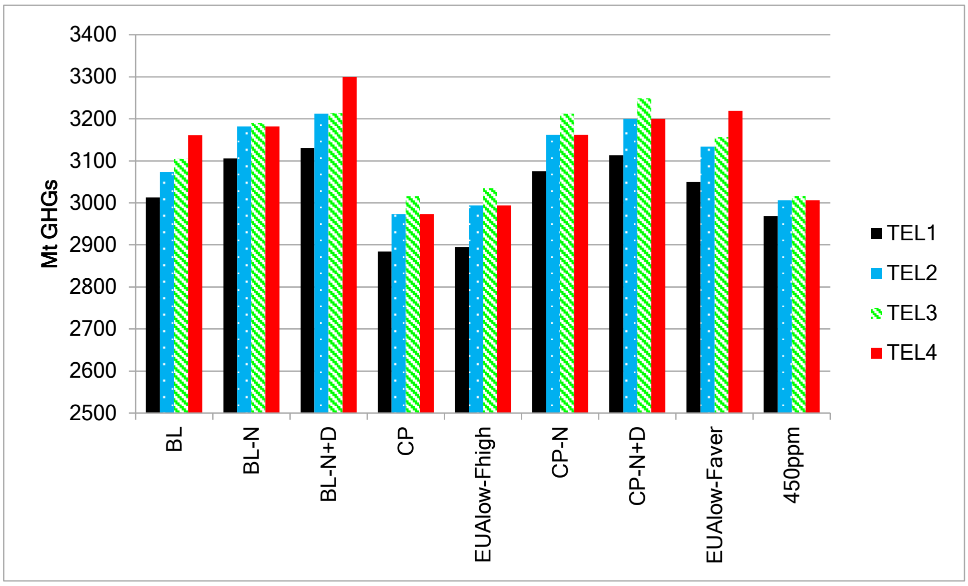


Note: Average over 5-year time span of annualized cost over (for instance, the 2020 value corresponds to the average of annual annualized cost from 2018 to 2022). The difference in the cumulative sum of total annual annualized costs from 2020 to 2050 is −€26.5bn (BL-N), −€25.4bn (BL-N+D), −€18bn (EUAlow-Faver), +€13.6bn (CP-N), +€14.6bn (CP-N+D), +€24.4bn (EUAlow-Fhigh), +€38.5bn (CP), and +€47.6bn (450 ppm), compared to the TEL2 BL reference case. For a comparison, 1 bln. € in 2020 corresponds to about 0.5% GDP predicted for the same year.

3.5.2.4. Greenhouse Gas Emissions

Figure 26 shows the cumulative GHG emissions over 2015–2050 in all scenarios. TEL1 results in the lowest magnitude of cumulative GHG emissions across all assumption sets, and they are smaller by 37 to 99 Mt GHGs compared with the TEL2 counterparts depending on the assumption set. The new policy has only a negligible effect on annual GHG emissions. In relative terms, annual GHG emissions with the ban on coal mining are only 0.2 to 6% smaller than the GHG emissions involved with TEL2.

Figure 26 Cumulative GHGs emissions, Czech Republic, 2015–2050.



There are minimal differences in the magnitude of the cumulative GHG emissions among the three policies that (may) revoke the mining limits (TEL2, TEL3 and TEL4) in scenarios without new nuclear reactors (BL-N) and with very high EUA prices (450 ppm) that may likely achieve the 450 ppm target. TEL2 and TEL4 will result in the same level of cumulative GHG emissions as well, when the price of fossil fuels will be high (CP, CP-N, CP_N+D and EUAlow-Fhigh). It means that the complete revocation of the Territorial Environmental Limits (TEL4) will not affect GHG emissions if a strict climate mitigation policy is implemented or fossil fuel prices are high; that is, if coal use responds to higher prices.

Lifting the coal mining limits more in TEL3 will yield higher cumulative GHG emissions than lifting the limits partially (TEL2) across all assumption sets, from 2 Mt in BL-N+D up to 50 Mt in CP-N. Lifting the limits completely (TEL4) will result in the highest GHG emissions among all TEL variants when EUA and fuel prices will be low (EUAlow-Faver) or if the lifetime of the Dukovany nuclear power plant is not prolonged (BL-N+D) – by 85–88 Mt compared to TEL2. Despite the higher usage of brown coal, cumulative GHG emissions are also lower with a high price of fossil fuels (CP and EUAlow-Fhigh) compared to other assumption sets, especially due to lower emissions from transport after 2030 (the energy sector is responsible for less than 70% of GHG emissions in the Czech Republic.).

3.5.2.5. External Costs

Using the ExternE's Impact Pathway Analysis, we quantify the external costs attributable to air quality pollutant emissions. These emissions are associated with adverse health impacts, such as respiratory and cardiovascular illnesses, cancers or premature mortality (Ščasný & Máca, 2016), impacts on buildings and materials, crops or ecosystems (Preiss et al., 2008;

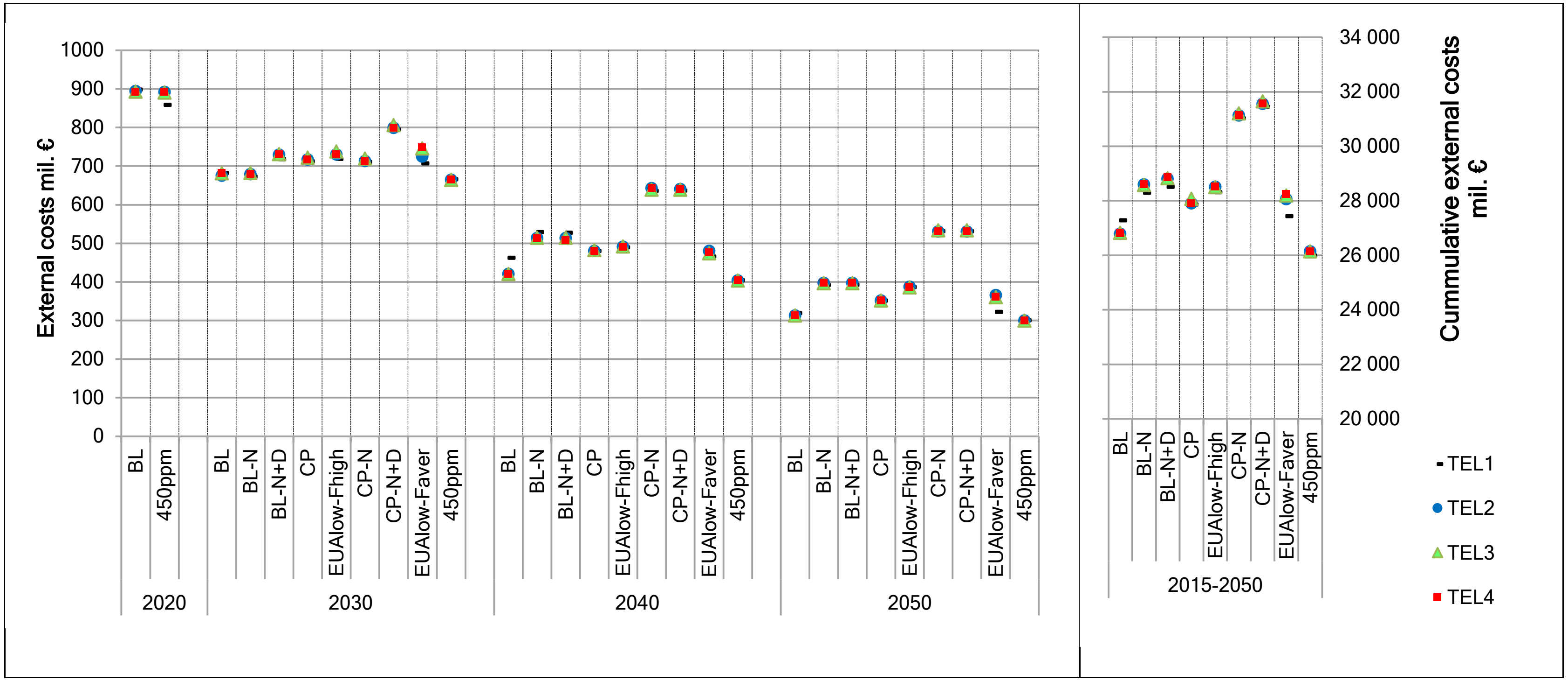
Ščasný et al., 2015). In this study, however, only emissions of SO_2, NO_x and particulate matters released from district heat and power generation are considered. The presented results are based on one (constant) damage factor value, regardless of when emissions will be avoided. Human health effects account for approximately 85% of total external costs. Biodiversity impacts, impact on crops and materials account for 9, 2, and 4 percent, respectively. Climate change impacts due to greenhouse gasses are quantified through the social costs of carbon (SCC), using a value of €19 per ton CO_2, similarly as in Weinzettel et al. (2012). Tol, (2013) provides an exhaustive survey of the literature on the damages of climate change, analysing over 588 estimates from 75 published studies. The author finds the mean estimate of the social cost of carbon to be about \$196 per metric ton of carbon (63 2012 EUR per ton CO_2), with the modal estimate at \$49per ton of carbon (16 2012 EUR per ton CO_2); see more in (Alberini, Bigano, Ščasný, & Zvěřinová, 2018).

Due to already tight air quality concentration limits that are expected to be enforced as of 2020, the effect of the three TEL policies on the external costs will not be very large. Thanks to policies already implemented, the magnitude of the external costs is in fact decreasing over time in all scenarios, starting at the level of approximately €900 million a year in 2020 and reaching €300–535 million a year in 2050.

Compared to the damage caused by TEL1 baseline policy, the largest magnitude of the effect can be expected for TEL3 policy if low EUA and fuel prices are anticipated (EUAlowFaver) – under these assumptions TEL3 policy will deliver €808 million of damage more than TEL1. This effect will however appear over the entire period and so in relative terms the cumulative value corresponds to only 0.5% of yearly GDP in 2015. Keeping the ban in place (TEL1) would avoid damage up to €619 million (0.4% of 2015 GDP) over the entire period if TEL2 was not adopted and the largest magnitude of the benefits would be generated when medium prices of fuels and low EUA prices are assumed (EAUlow-Faver).

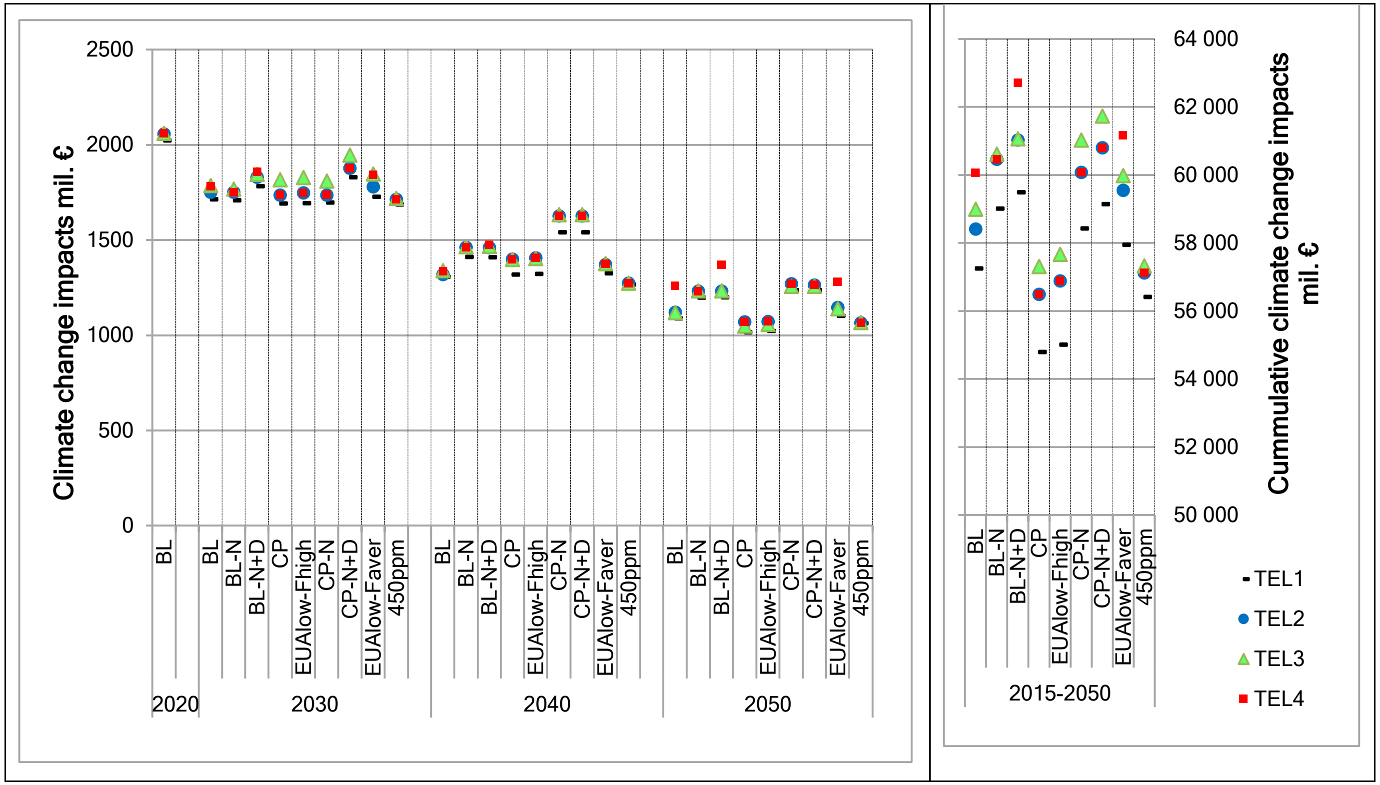
The magnitude of external costs varies across the assumption sets. In absolute terms, cumulative aggregate over 2015–2050 is within a range of €26 billion (450 ppm) to €31.6 billion (CP-N+D and CP-N), see Figure 27.

Figure 27 External costs attributable to air quality pollutants released from district heat and power generation, annual averages (left panel) and cumulative aggregate over 2015–2050 (right panel), in million euro



Note: For sake of clarity, assumption sets BL and 450 ppm in 2020 are displayed only, as the value in other assumption set is on the same level as in BL.

Figure 28 Impacts attributable to GHG emissions and to the whole energy balance, for selected years and cumulative figure



Note: The level of external costs is similar for all assumption sets in 2020. The share of GHG emissions from ETS sectors declines from about 60% in 2020 to a range of 30 and 55% depending on the assumption set. The climate change impacts due to GHGs are actually internalized through the EU ETS.

These values correspond to 16 and 20 per cent, respectively, of 2015 GDP or they may represent 0.1–0.5 per cent of annual GDP over the period. The 450 ppm set largely affects the power sector, implying the lowest magnitude of external costs and hence the largest value of environmental benefits for all four TEL's policies. On the other hand, scenarios without new nuclear reactors and with high prices of natural gas (CP-N, CP-N+D) result in the lowest avoided external costs and hence generate the lowest magnitude of benefits as nuclear energy is replaced mainly by coal.

The next figure displays climate change impacts attributable to the whole energy balance. We find that their cumulative magnitude varies across scenarios and assumptions more (€54.8bn to €62.7bn) than it is in the case of air quality impacts (€26bn to €31.5bn). Still, the magnitude of climate change impacts over the entire period corresponds to 34 and 39 per cent of 2015 GDP or may be in a range of 0.5–1.1 per cent of annual GDP. Energy-intensive processes other than heat and power generation contributes to this variation by one part, while the absence of any abatement technology for GHGs emissions adds the other part. In cumulative terms, climate change impacts are the lowest in TEL1 CP and the highest for TEL4 BL-N+D. On average, the restrictive policy variant TEL1 may lead to about €3bn lower impacts than the policy variant TEL4, with complete lifting of the limits.

The annual cost values have a decreasing trend from €2bn in 2020 to a range of €1bn and €1.37bn in all scenarios. They are the highest in scenarios with any new nuclear power plant. The TEL1 restrictive policy variant involves the lowest SCC across all TEL variants, both annually and cumulatively. High price of fossil fuels (in assumption sets CP, CP-N, CP-N+D and EUAlow-Fhigh) reduces GHG emissions and hence impacts. This is illustrated by the left panel in Figure 28, reporting the cumulative values.

3.6. Policy Implications

There are four main policy implications resulting from our analysis:

- TEL 2 policy that was adopted by the Czech government in September 2015 may have a more significant effect on the Czech power sector only if 1) no new nuclear power plant is built around 2035, or 2) the EUA price remains very low (<10 € up to 2025 and <27 € up to 2050) and the price of natural gas does not increase considerably at the same time (see EUAlow-Faver scenario). Recently adopted policy (TEL2) may on the other hand reduce fuel dependency and in particular import of low quality brown coal needed for the heating sector. However, the volume of brown coal imports is very small, amounting to 3 Mt a year that corresponds to 6% of total brown coal demand in 2015.

- There are two other policy options for lifting of the Territorial Environmental Limits further and beyond TEL2 that are still on the policy agenda of the current Czech government. Compared to the TEL2, both of these policy options (TEL3 and TEL4) would have a significant impact on the Czech energy system only if (1) the price of natural gas increases considerably; (2) the EUA price remains very low and the price of natural gas is not very high; and (3) no new nuclear blocks are built and the lifetime of the currently operated Dukovany nuclear power plant is not prolonged until 2035 at the same time (see BL-N+D scenario). Still, compared with the already adopted policy, the effect of the two least ecologically stringent policy proposals may change fuel mix in a magnitude of a few percentage points.

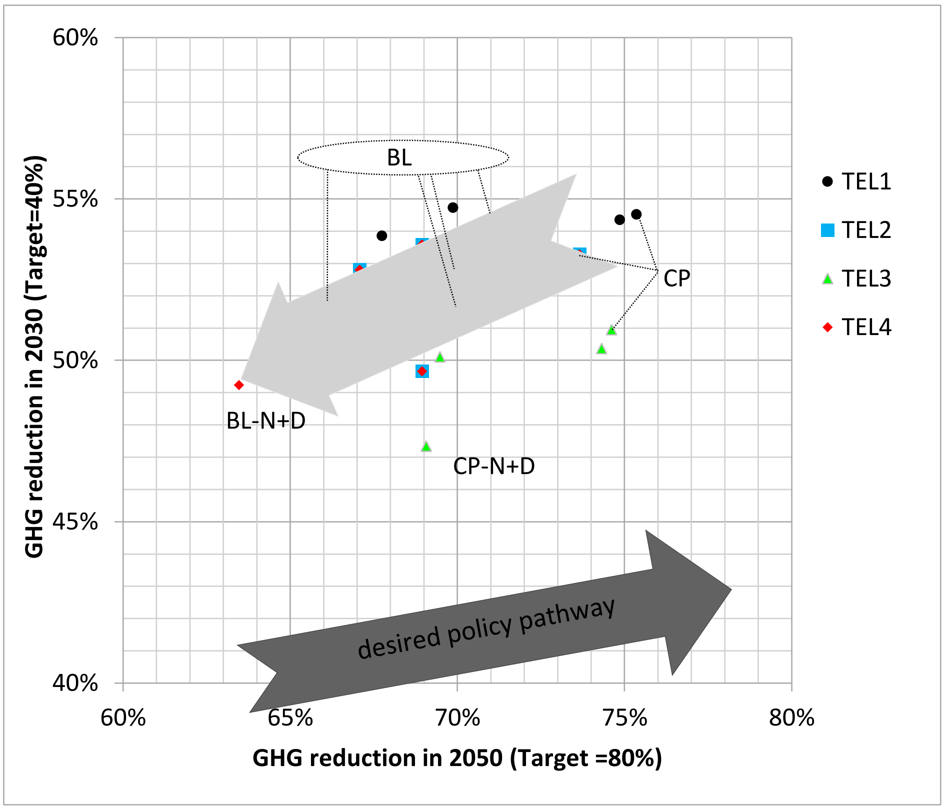
- Due to tightening air quality concentration limits in already implemented policy neither of the four TEL policies will have a significant effect on emissions of local air pollutants and hence related externalities attributable to the energy sector. However, policy that lifts the mining limits will have a considerably larger impact on GHG emissions and thus will result in adverse climate change impacts. Over the entire period, keeping the ban (TEL1) may lead to about €3bn lower damage than the policy that would lift the limits completely (TEL4). Lifting the limits on mining brown coal can be thus considered as very effective policy going against current trends in de-carbonizing the economies and energy systems in particular.

- The Czech Republic is well on the way to fulfilling the 2030 target of a 40% reduction of GHG emissions compared with the 1990 level. Based on our analysis, the GHG emission reduction should be achieved at least at the level of 47% in the worst case in the TEL3 CP scenario. If the government had agreed on keeping the TEL1 variant, the reduction potential would have been up to 55%. But even for the newly agreed policy (TEL2), the GHG emission reduction potential ranges between 50 and 54 percent in 2030 as shown in Figure 29.

- The 80% GHG emission reduction target for 2050 will not be achieved by any policy and under any assumption scenario, even if the territorial mining limits were kept (TEL1). Due to the high price of oil resulting in a high emissions reduction in the transport sector, there is the biggest GHG emission reduction potential for the CP assumption set, yielding an approximate 75% reduction in TEL1 and TEL3, or a 74% reduction in TEL2 and TEL4 policy variants. The lowest GHG emissions reduction in 2050 is achieved in scenario TEL4 BL-N+D; that is, when the mining restrictions are completely lifted, when operations at the older Dukovany nuclear power plant are not extended and no new reactors are build, with prices of fuels and EUA in the middle of the range.

- Building a new nuclear power plant would not lead to higher total annualized costs under the very high fossil fuel prices only (CP-N and CP-N+D).

Figure 29 GHGs emissions reductions in 2030 and 2050, the 2030- and 2050-targets compared to the 1990 reference level.



Note: Green triangles are always lower than blues and reds, indicating TEL3 is worse to reach the 2030 40% target than TEL2 (blue) and TEL4 (red). The reds are always more on the left (or at the same position) as green or blue, indicating missing the 2050 target most. The black circles are always on the top and on the right, showing that TEL1 has the best performance to reach both 2030 and 2050 targets.

As the current State Energy Policy (MPO, 2015b) assumes installation of new blocks of a nuclear power plant, there is no need for further lifting of the Territorial Environmental Limits. Only if the European effort to mitigate climate change was unsuccessful and the EUA price was low, some of the additional brown coal outside the limits could be used.

3.7. Conclusions

In response to the massive destruction of the landscape and heavily polluted air due to domestic brown coal burning, in 1991 the Czech government decided to restrict brown coal mining to specified territories in the North Bohemia coal basin, the so-called Black Triangle. Many other countries have restricted usage of coal, especially brown coal and lignite, to reduce greenhouse gasses for the last two decades, as a response to climate change impacts. The revocation of Territorial Environmental Limits on mining brown coal mines in 2015 by the Czech government (TEL2 variant) represents an opposing policy, going against current modern policy trends. Our modelling shows that lifting the limits will lead to 400–1317 PJ higher brown coal consumption and thus to higher GHG emissions by 37–99 Mt over the period 2015–2050 compared to a policy that would maintain restrictions on the brown coal mining (TEL1). This range is quite large and stems from different assumptions concerning fuel and EUA prices and the deployment of nuclear power assumed in this paper.

The modelling results are more sensitive to price assumptions than to different deployments of nuclear power (compare with Rečka & Ščasný (2018). In fact, only under the highest EUA price assumption, the newly accessible brown coal – being stranded within the limits until 2015 (TEL2) – will not be domestically used completely, but the volume of imported brown coal varies. On the other hand, in the case of completely abandoning the mining limits (TE4), the share of domestic usage of newly accessible brown coal declines with increasing EUA price from 80 to 35 percent with regard to nuclear energy development.

In short, it is not lifting the Territorial Environmental Limits on brown coal reserves that will have large impact on the fuel mix of power generation. Rather it will be the (internal) decision of the Czech government concerning nuclear energy use in the Czech Republic in the future, and even more the (external) factors, such as market prices of fossil fuels and price of EUA. The TEL lifting will also not play a significant role in determining the total costs of the Czech energy system. The lifting of the TEL will not have a large impact on the magnitude of the external costs attributable to district heat and power generation either, as strict concentration limits on air quality pollutants have been already implemented. Again, the governmental decision about development of nuclear energy and market prices of the EUA and/or fossil fuels are the key factors of the fuel mix, economic costs and health externalities.

Any of the three policy options that lift the Territorial Environmental Limits on brown coal reserves will complicate the 2050 GHG emissions reduction target to be achieved in the Czech Republic, without additional expensive measures to be implemented outside the ETS sectors. Moreover, the Czech Republic is committed to achieving a 13% share of renewable energy in total gross energy consumption in 2020 (MŽP, 2012) and almost 20% in 2030 (indicative target (Resch, Panzer, Ortner, & Resch, 2014). In combination with the present low public support provided for renewable sources it could be also difficult to reach these targets when new brown coal reserves will be accessible (since 2014 the Czech government no longer subsidises new photovoltaic and biogas power plants with feed-in-tariffs or a quarantined price, and this subsidies to all other new renewable sources, except small hydro ceased from 2016 (Parliament of the Czech Republic, 2012) – partly as a result of massive subsidising in 2009 and 2010 as analysed in Průša, Klimešová, & Janda (2013). On the other hand, an investment subsidy for photovoltaic in households was introduced in 2016.

Our analysis focuses on the period between 2015 and 2050 since very few data beyond 2050 are known or at least forecasted. In this context it is worth mentioning that the entire revocation of the Territorial Environmental Limits in variant TEL4 would increase brown coal mining even after 2050, by about 105 PJ per annum till 2074 (MPO, 2015a). Moreover, a more environmentally-friendly technology mix may also generate environmental benefits beyond 2050, as the technological lifetime of some technologies that will be installed up to 2050 will be longer than the period up to 2050. Neither of these effects are considered in the presented analysis.

The main limitation of our analysis is exogenous energy demand and further assumptions on the Czech energy market that follow the Czech 2015 State Energy Policy. Following the 2015 SEP allows us to better disentangle the effect of the Territorial Environmental Limits policy variants, or fuel and EUA prices from the possible effects on the supply side of the energy system that are not incorporated into the SEP. There are other important factors that may affect energy efficiency improvements, including increasing environmental awareness and concern (Urban & Ščasný, 2016) or factors that may minimise the energy efficiency gap. Energy efficiency or demand side management is not a part of the presented model. Instead, we follow the aggregate energy demand, as defined by the 2015 SEP, that also allows us to avoid double counting of energy efficiency improvements that are already accounted for in the calculations by the SEP. As a result, consumer behaviour is taken into account only implicitly through the modelling assumptions and not as a part of the model structure. We will focus on this limitation in our future research.

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4. Influence of renewable energy sources on transmission networks in Central Europe[1]

Abstract

This article focuses on the influence of increased wind and solar power production on transmission networks in Central Europe. The German Energiewende policy, compounded by insufficient transmission capacity between northern and southern Germany and the existence of the German-Austrian bidding zone contribute markedly to congestion in the Central European transmission system. To assess the exact impact on the transmission grid, the direct current load flow model ELMOD is employed. Two development scenarios for the year 2025 are evaluated on the basis of four representative weeks. The first scenario focuses on the effect of the Energiewende policy on transmission networks, the second scenario excludes nuclear phase-out and thus assesses the isolated effect of increased feed-in.

The results indicate that higher feed-in of solar and wind power increases the exchange balance and total transport of electricity between transmission system operator areas and the average load of lines and volatility of flows. Solar power is identified as a key contributor to the volatility increase, wind power is identified as a key loop-flow contributor. Ultimately, we conclude that German nuclear phase-out does not significantly exacerbate volatility or loop-flows.

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4.1. Introduction

This paper investigates a contradiction between two major EU energy policy directions: on one hand creating a unified energy market, on the other, promoting renewable energy, where the problems with the accummulation of renewable electricity in electricity transmission networks provide strong policy incentives to close national networks and refuse the transfer of electricity from other countries during high-production events (Huppmann & Egerer 2015). In order to address this problem, we use the ELMOD non-linear optimization model, which maximizes social welfare under a number of constraints. We analyse the impacts of increased renewable energy feed-in and nuclear phase-out on cross-border grid congestion in Central Europe (CE) and on volatility growth in transmission networks in CE. The important contribution of this paper is that, unlike many others, it focuses on the whole CE region in the same detail as Germany and particularly elaborates on the influence of individual components of the German Energiewende policy (i.e. renewable energy promotion and nuclear phase-out) on the whole area. Also, this paper stresses the importance of the German - Austrian bidding zone which has been mostly neglected in research to date. This paper uses a "critical scenario approach". This means that the results must be interpreted in the context of what would be the impact of electricity flows on the grid if no change was implemented in the grid development.

The main factors in the renewable energy side of the policy conflict are the EU 20-20-20 targets (European Commission 2009) and even more ambitious targets of 2030 climate energy framework (at least 40% cuts in greenhouse gas emissions (from 1990 levels), at least a 27% share of renewable energy and at least a 27% improvement in energy efficiency) (European Commission 2014). The significant factor on the market integration side of the controversy is the effort to create a European Energy Union, officially launched in 2015 (European Commission 2015).

The development of variable renewable energy sources (VRES) in Germany caused severe problems with the transmission network in the CE region, defined as Germany, Czech Republic, Slovakia, Poland and Austria in this paper. Excess production in the north has to be transported to the consumption centres in the south of Germany, to Austria and other energy deficient countries in southern Europe. The extant German grid is unable to accommodate such a big feed-in of intermittent renewable energy and, therefore, becomes congested. As a result, electricity flows through the systems of adjacent countries - Poland and the Czech Republic, causing congestion in their grids as well. These problems are exacerbated by market integration, in particular by the existence of the German-Austrian bidding zone which enables these two countries to trade electricity disregarding the physical grid constraints as illustrated in Figure 30. While this single bidding zone also includes Luxembourg, we refer to it as the German-

Austrian zone because of the Central European focus of this paper. Czech and Polish transmission system operators (TSOs) have responded to this by insisting that the German-Austrian bidding zone should be broken up (ČEPS 2012), a move which was also supported by the Agency for the Cooperation of Energy Regulators (ACER) (ACER 2015), or even for dividing Germany up into several zones. The TSOs have also attempted to solve this problem by installing phase-shifting transformers that should be able to stop physical electricity flows in case of emergency.

Nevertheless, in January 2016, the Director of DG Energy declared that the European Commission is against the split of the biding zone as it considers this step to be "meaningless" (Kamparth 2016).

While many academics have conducted research on the topic of the influence of renewables on the spot and forward market prices of electricity (Cludius et al. (2014); Ketterer (2014)), public budgets and consumer prices (Janda et al. (2014); Průša et al. (2013)) or the power system in general (Blesl et al. (2007); Havlíčková et al. (2011); Rečka & Ščasný (2016; 2013); Ščasný et al. (2009)), less attention has been paid to the equally important issues concerning transmission networks. The majority of the literature assesses the transmission network issues only in the context of Germany (Kunz (2013); Kunz & Zerrahn (2015); Schroeder et al. (2013); Egerer et al. (2014); Dietrich et al. (2010)).

Figure 30: Stylized map of the situation in CE

Source: Authors, based on maps from ENTSOE (2016)

For the transmission network analysis in this paper we use the most suitable state-of-the-art model, ELMOD. Since its initial publication in Leuthold et al. (2008), this model has been applied most frequently to the analysis of market design (Neuhoff et al. (2013); Egerer et al. (2016)), the influence of renewables on transmission networks (Egerer et al. (2009); Schroeder et al. (2013)) including grid and power plant investment decisions (Leuthold et al. (2009); Dietrich et al. (2010); Egerer et al. (2013)), uncertainty and stochastic effects (Abrell & Kunz (2012)) and congestion management issues (Kunz (2013); Kunz & Zerrahn (2015; 2016)).

The literature on transmission networks and the grid in CE is significantly less extensive. Apart from the above-mentioned ELMOD literature, there are a few other articles which deal mostly with optimal grid extension or the integration of renewables into the grids. Nevertheless, these focus on Germany (Winkler et al. 2016; Singh et al. 2015) or Europe as a whole (Fürsch et al. 2013; Majchrzak et al. 2013; Schaber et al. 2012a;b). The grid-related literature in Poland has most frequently examined the possibilities of phase-shifting transformers (Korab & Owczarek 2016; Kocot et al. 2013).

The literature focusing wholly on the CE region is very sparse. A few examples include recent articles from Singh et al. (2016), analysing the impact of unplanned power flows on transmission networks, Eser et al. (2015), assessing the impact of increased renewable penetration under network development and Kunz & Zerrahn (2016) focusing on cross-border congestion management.

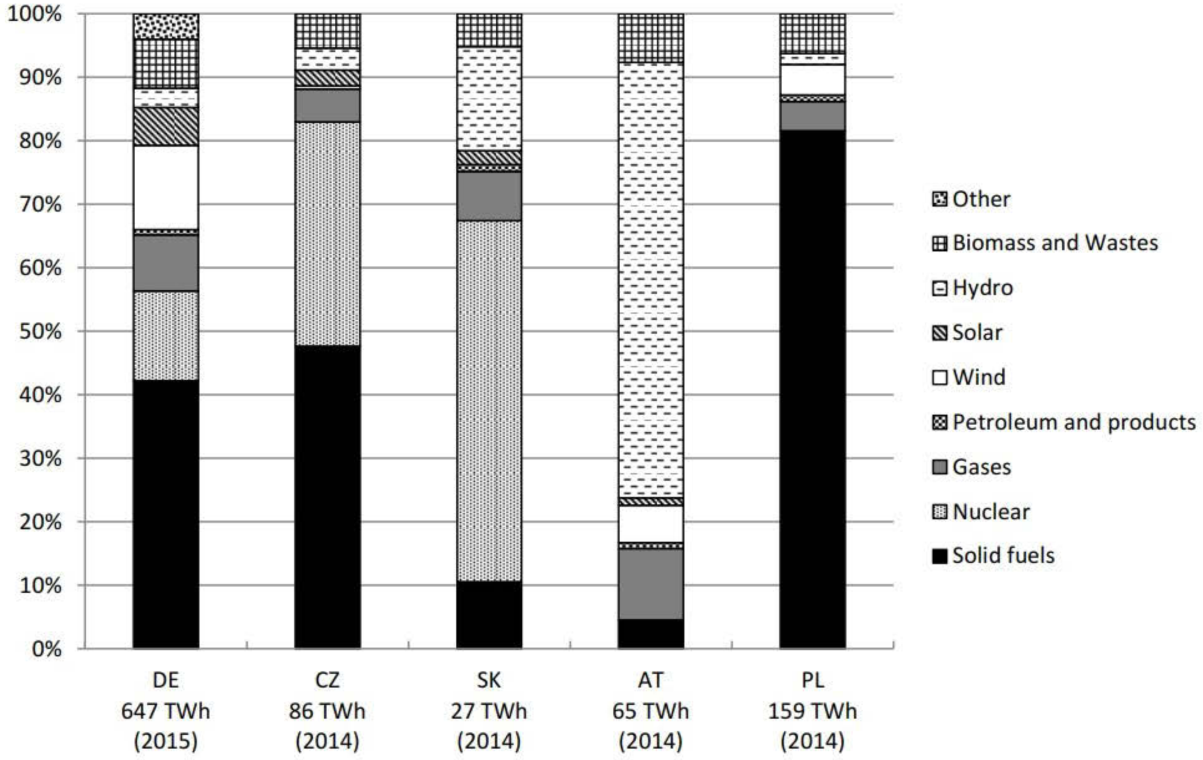
This paper is structured as follows: Section 2 provides an overview of power and transmission systems in CE. Section 3 explains the ELMOD model and the susequent section 4 describes the data. Section 5 introduces our base scenario and two development policy scenarios, section 6 presents and interprets the results and lastly section 7 concludes.

4.2. Overview of power and transmission systems in Central Europe

4.2.1. Electricity production

Electricity production in CE is heterogeneous and as are the energy reserves, potentials and policies in each country of this region. Figure 31 illustrates the differences in generation structures among the CE countries in 2014 (2015 in the case of Germany).

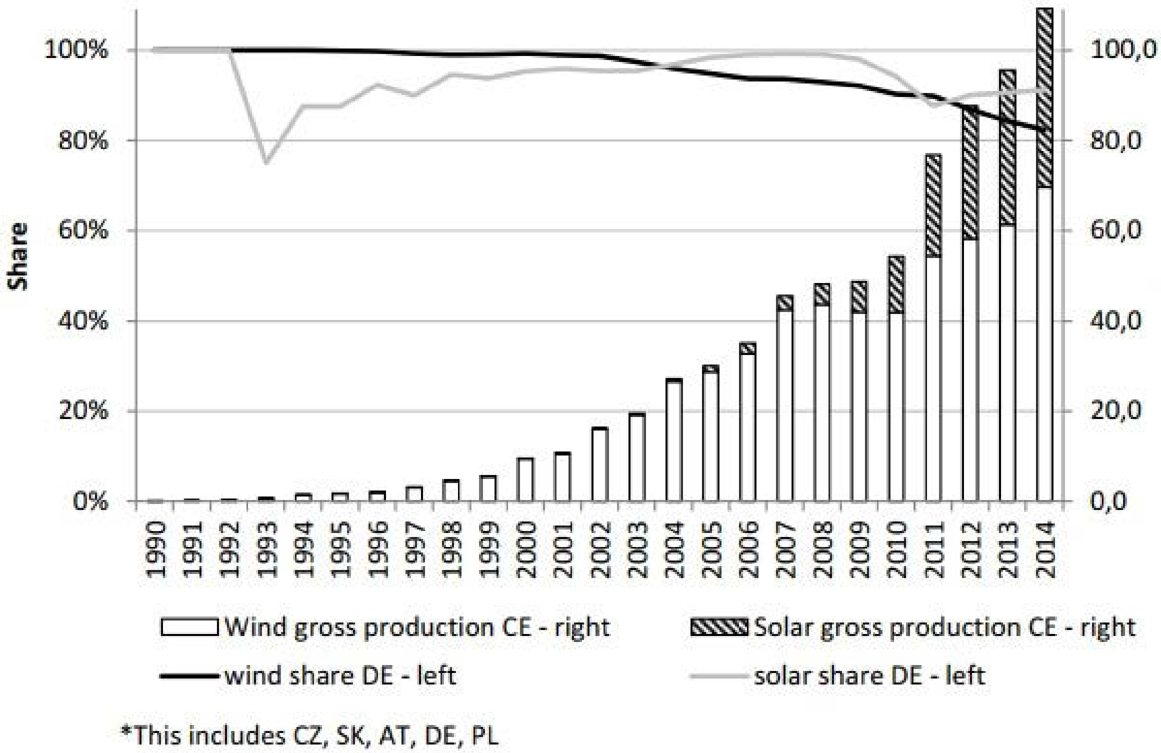
Figure 31: Electricity production by fuel type in CE countries



Source: European Commission, DG Energy (2016a)

Out of 651.6 TWh of electricity produced in Germany during 2015 (BMWi 2016) the share of solid fuels is 42% and renewables account for 30 %. The most important German renewable sources are on shore wind turbines, biomass and solar power plants. At the end of 2014, 46.72% of total installed capacity can be assigned to renewable energy sources (RES). This is the second highest number in the CE region after Austria. Germany has been a net electricity exporter since 2003 and it exported 50.1 TWh of electricity in 2015 (BMWi 2016). Due to its size, the German energy system dominates the CE region. Thus, policies implemented in Germany have profound affects across the whole region. This is particularly true for wind and solar production, as illustrated by Figure 32. Out of 86.3 TWh of electricity generated in the Czech Republic during 2014 (Energy Regulatory Office 2015) the biggest contributors were solid fuels (48%) and nuclear power plants (35%). At the same time, the net balance with foreign countries accounted for 16300 GWh of export which making the Czech Republic the third largest exporter of electricity in Europe (Energy Regulatory Office 2015).

Figure 32: Wind and solar production in CE* and Germany's share



Source: Own, data European Commission, DG Energy (2016a)

Moreover, the balance with other countries has not dropped under 11 TWh since 2002. With 83 % share of RES of total electricity generation (65.4 TWh in 2014), Austria is a leading nation in CE's ecological production. Austria has been a net importer since 2001 with a net electricity import of 9.275 TWh in 2014 which corresponded to 13.46% of its 2014 inland consumption (European Commission, DG Energy 2016a; E-CONTROL 2016). 2871 MW of intermittent installed capacities (wind and solar) as of 2014 corresponded to 12% of total installed capacity. It is important to note that the majority of Austrian hydro power is pumped storage power plants (7969 MW or 58.73 % of installed hydro) (E-CONTROL 2016). Slovak electricity production (27.4 TWh in 2014) and consumption is the lowest in the CE region. The greatest share (57%) came from nuclear power plants and hydro power plants (16%). Similarly to Austria, Slovakia has a low share of fossil fuels in the total electricity production (20%). Slovakia has been a net electricity importer since 2006 when it had to shut down part of the Jaslovske Bohunice nuclear power plant. In 2014, imports accounted for 1.1 TWh representing 3.9% of Slovak consumption. The share of imports varies substantially between years (European Commission, DG Energy 2016a; Ministersvo hospodárstva Slovenskej republiky 2015).

Of 159.3 TWh produced in Poland in 2014, 81 % was generated by coal fired power plants, of which hard coal power plants supplied 80.24 TWh and lignite power plants 54.2 TWh (PSE 2015b). The second most utilized sources were then biomass and wind power plants (6% and

5% respectively). Wind power plants ensured significant capacity growth in recent years which can be attributed mainly to the fact that the Baltic sea and surrounding regions offer suitable conditions for wind production. Poland is structurally an electricity exporter.

Nevertheless, in 2014 we can observe imports of 2.16 TWh which accounted for 1.36% of annual consumption in 2014 (PSE 2015b).

4.2.2. Transmission systems and grid development

The German transmission grid is divided between four TSOs: TenneT, Amprion, 50Hertz Transmission and TransnetBW. The TSOs are supervised and regulated by the German federal network agency, Bundesnetzagentur (BnetzA) which ensures discrimination free grid access. Since 2011, it has also played an essential role in implementing the grid expansion codified in the Grid Expansion Acceleration Act (NABEG).

The German transmission grid faces severe congestion problems. In the past, electricity generation was based on two criteria: Availability of resources in the vacinity and location close to the centre of demand. The boom of renewables has, however, changed the situation dramatically. In Germany, centres of electricity consumption are situated mostly in the south and west of Germany but regions suitable for most economic production VRES are in the north. The electricity generated there must therefore be transported over long distances to the consumers. In the process, the existing network frequently reaches its capacity limits (Bundesnetzagentur 2015). This represents a clear challenge for the old, supply-adjustment based grid model. More dynamic and agile set-ups including demand balancing, electricity storage devices installation and re-dispatching will be necessary to handle the situation successfully (Pollitt & Anaya 2016).

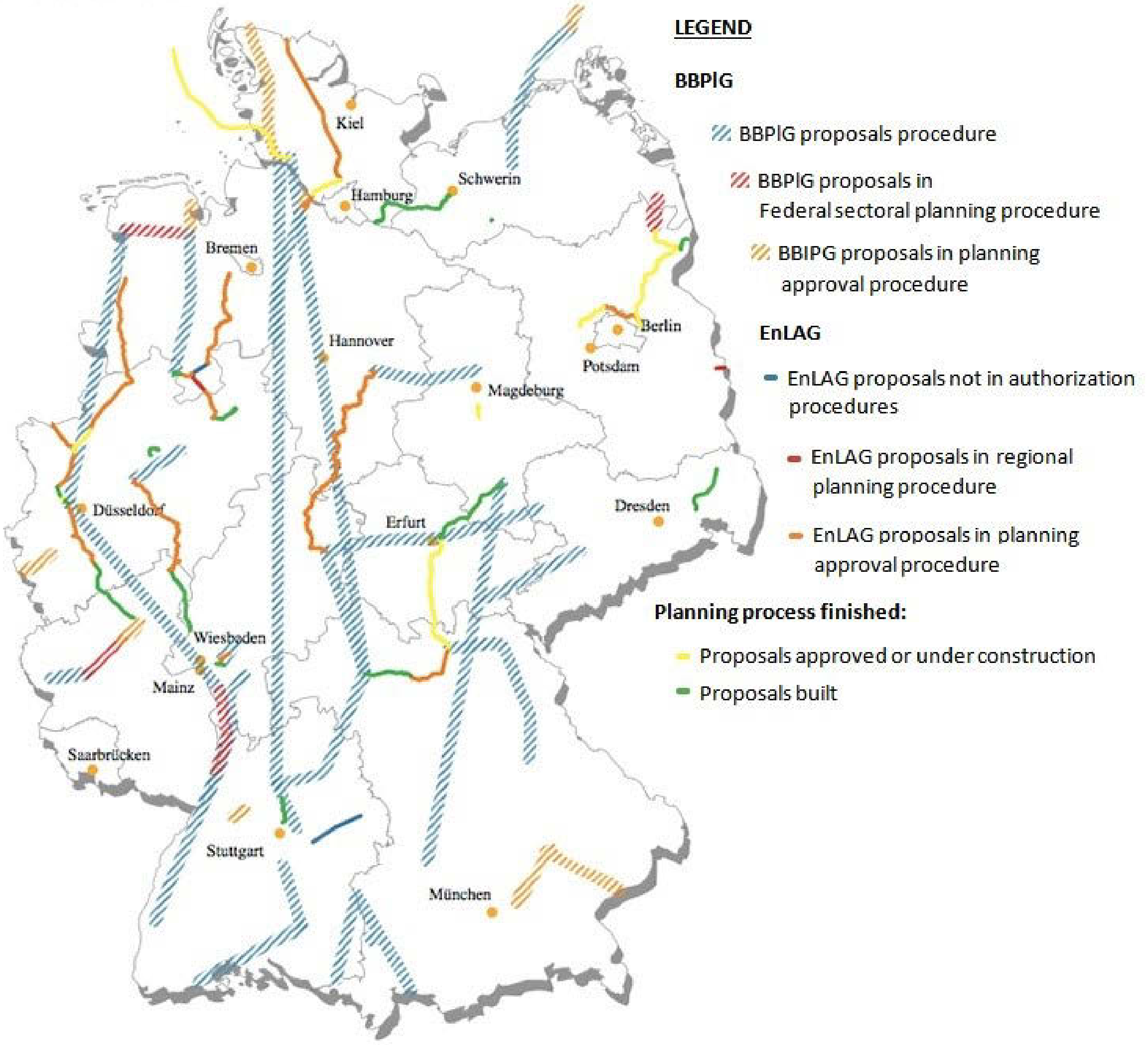
The costly (Bemš et al. 2015) planned nuclear phase-out furthermore contributes to north-south grid pressures. Nuclear power plants are mostly located in southern regions, Bavaria and Baden-Wurttemberg. 8386 MW of nuclear installed capacity in these two states should be disconnected from the grid by 2022. The loss of capacity is not expected to be fully offset by newly installed capacities, a result of the area’s limited RES potential (Flechter & Bolay 2015).

The need to strengthen the infrastructure in the north-south direction is therefore unquestionable, and is also the stance taken by German authorities (BMWi 2015a) and especially neighbouring TSOs as described below. The grid expansion agenda is backed by two

German laws – the Power Grid Expansion Act (EnLAG) from 2009 and Federal Requirements Plan Act (BBPlG) from 2013.

Nevertheless, the volume of the infrastructure extension as well as the realization itself seem to be a matter of controversy which has halted the process of construction. EnLAG legislature specified 23 mostly north-south transmission lines 1876 km in length that need to be urgently built to preserve the stability of the system in an environment of increasing RES production. The construction should have been finished by the end of 2015 (Flechter & Bolay 2015). Nonetheless, in the third quarter of 2016, only 3 kilometres of lines had been built which totals around 650 km including previous construction (35% of the planned length). Estimates now calculate 45% being built by the end of 2017 (Bundesnetzagentur 2017). The BBPlG, which came into effect in July 2013, added another 36 planned extension lines, 16 of which are considered of cross-regional or cross-border importance. Corridors of future networks are now determined and a public discussion about the exact tracing is in progress (BMWi 2015c). As of the third quarter of 2016, 400km were approved but only 80km of lines were realized (Bundesnetzagentur 2017).

Figure 33: Future extension of German transmission lines



Source: BMWi (2015c)

Construction activities thus suffer from major project delays which can be primarily ascribed to the negative public opinion about (overhead) lines. The general public refuse the grid construction in the vicinity of their dwellings and demand the underground solutions as far as possible. Schweizer & Bovet (2016) conclude that the approval rates for new grid construction among German public are very high at national level, but decrease when the question is asked in a local context, where 60% of people would accept overhead grid expansion if a minimum distance of 1 km to their homes was guaranteed (85% for underground solutions).

As a result of public resistance, a decision was taken concerning underground-redeployment of some major grid expansion projects. The most significant example is the SuedLink project - a key north-south power link. However, the cost of such action is tripling the construction costs and delaying completion to beyond the year 2025 (Franke 2017). Consequently, it seems that grid enhancement even with the target of 45% is foreseeable.

The Czech transmission system still reflects the design at the time of completion in the 1980s. Investments to the grid enhancement and reinforcement need to be implemented so that the grid is able to cope with upcoming challenges (ČEPS 2016). Rapid growth in installed capacity of Czech solar power plants (Luňáčková et al. 2017; Sokol et al. 2011) between 2008 and 2012 caused problems in Czech grid. In this period, the Czech cumulative solar capacity grew a little more than 50 times and during 2009 and 2010 alone, applicants asked the distribution companies to connect up to 8000 MW (Vrba et al. 2015) which resulted in a request by the Czech transmission system operator, ČEPS, to temporarily halt approvals of new capacities (ČEPS 2010). Thus the network stability was endangered already in 2010 (1727 MW of solar and 213 MW of wind installed) (EGU Brno 2010) because of Czech domestic reasons. As a result, feed-in tariffs were decreased up to 50% and later were completely abolished for most RES built after 2014 (Vrba et al. 2015). After this, approvals for connections to the grid were once again allowed as of January 2012 (Klos 2012).

The process of planning the further development of Czech grid is mostly driven by the "Ten-year investment plan for the development of the transmission system" to be implemented between 2015 and 2024: its main goals are the expansion and upgrade of existing substations, construction of second circuits on selected lines as well as construction of several new ones. Installation of phase-shifting transformers at Czech-German interconnectors were finished in March 2017 at the approximate cost of 74 m EUR (ČEPS 2017). The total volume of investments during this development plan is estimated to reach 1.66 bn EUR (ČEPS 2015).

The Austrian transmission network, operated by the company APG, plays a key role in Central Europe as it is a crucial cross-road for transport of electricity from the Czech Republic and Germany to south-eastern European countries. Since 2015 the new Austrian "Ten year Network development plan" focused on grid reinforcement and expansion measures, upgrade of existing lines to higher voltage levels, construction of substation and transformers as well as 370 km of new transmission lines (APG 2015).

The Slovak transmission network, like the Czech one, was for a very long time part of the common Czechoslovakian system which was developed as one fully integrated system. This explains the absence of bottlenecks on the Czech-Slovak border and extraordinarily high level of interconnection at 61 %. The Slovak grid is important in the international context as Czech exports to Slovakia are almost all passed further along to Hungary. (In 2014, 9392 GWh of electricity was imported from the Czech Republic and 9356 was exported to Hungary (Ministersvo hospodárstva Slovenskej republiky 2015)). Also the Slovak grid will be subject to reinforcements and upgrades. In 2014, SEPS issued a "Ten year development plan for the years 2015-2024". In this plan, investments reaching 564 m EUR are outlined. They concern mostly internal advancement of infrastructure as well as expansion of cross-border transmission lines, particularly on Slovak-Hungarian borders. All other border profiles are not included in projected investment plans as their capacity is sufficient (SEPS 2014).

The Polish transmission network suffers from very low density in northern and western areas as well as a very low interconnection level of only 2% causing severe electricity transmission problems. Very often, congestion and reaching the upper limits of the lines occur. The most critical situations appear on Polish-German border where there are only 4 interconnectors with a voltage level 220 kV. The contemporary "Development Plan for meeting the current and future electricity demand for 2016-2025" responds to this and the existing interconnectors are planned to be upgraded to 400 kV levels. Moreover, after the grid in western Poland is reinforced by 2020, a new interconnector is projected after 2025. PSE also plans major infrastructure enhancement across Poland, the precondition for the successful connection of anticipated new power plants, mostly wind, gas and coal fired. Outlays in the first half of the period should reach 1.59 bn EUR, then 1.43 bn EUR (PSE 2015a) between 2021-2025.

4.2.3. Market design description and cooperation setup

Market design is another important factor that influences power and transmission systems in CE. With the current technological state of the art, the possibilities for electricity storage are extremely limited when economic viability is taken into account. Consequently, flawless grid operation requires equality of supply and demand at any particular time and place. TSOs are responsible for ensuring such equilibrium by forecasting demand, scheduling supply and balancing the deviations. The design of bidding zones is an important parameter of the electricity market. Bidding zones are frequently set to correspond to national borders that reflect the nature of the infrastructure development. Setting up cross-zonal bidding areas has several advantages as well as disadvantages. The main benefits are the equality of the price of wholesale electricity in the bidding zone, higher liquidity, effectiveness and transparency of the market as well as implicit capacity allocation (ACER 2015). This is based on the fundamental assumption of having sufficient transmission capacity within the bidding zone. The main drawback is that cross-border internal flows in a huge bidding zone cannot be controlled, implying that the flows also have an impact on adjacent bidding areas (ČEPS 2012). The usual reaction of responsible TSOs is a decline of cross-zonal tradable transmission capacity (Net Transfer capacity (NTC) which is the main determinant of free cross-border commercial transmission capacities between particular zones). As such, proper bidding zone delineation is crucial for efficient functioning of the system; otherwise, the zone can represent an artificial bottleneck in the electricity market.

Austria, Germany and Luxembourg are exemptions from the single-country bidding zone and, since 2005, have formed a major bidding zone in Central Europe. The formation was merely unilateral with no attention paid to the side-effects imposed on the adjacent countries, the Czech Republic and Poland (Bemš et al. 2016). While the zone guarantees unrestricted trading and common electricity prices to all participating countries, lack of internal transmission capacity causes significant negative overflows to the transmission systems of neighbouring countries. Mostly for these reasons, there are attempts to split the German-Austrian bidding zone or even to split Germany into two zones to terminate the source of the grid's artificial bottleneck.

4.3. Methodology

This study applies the state-of-the-art DC load flow model ELMOD also used in Leuthold et al. (2012) and Egerer et al. (2014). The mathematical formulation can be found in the Appendix C and is based on an optimization problem that maximizes social welfare using hourly data after taking into account the technical and physical peculiarities connected to electricity. The maximization problem is solved for the whole area at once which is equivalent to the assumption of one TSO operating entire area. The model is solved in GAMS (General Algebraic Modeling System) using the CONOPT solver.

The model applies a welfare maximizing approach with a target function maximizing consumer and producer surplus (see eq.1 in the Appendix C). The model is constrained by a nodal energy balance which states that the difference between generation and demand at a specific node, net of storage, demand shifting and load in- or outflow, must be zero (eq.3). A generation capacity constraint incorporates technical generation limits of each plant type at each node and time (eq.4). Line flow restrictions are taken into account (eq. 5) - (eq.7). Electricity inputs include total generation from controllable power plants $\sum_c g_{nct}$, wind generation G_{nt}^{wind}, solar generation G_{nt}^{solar} and storage power plant release PSP_{nt}^{out}. Moreover, the parameter on the maximum thermal limit of transmission line inherently incorporates the system security criterion by allowing for some reliability margin. The flows over a particular line in a given time are modelled (eq. 5) and the phase angle for an arbitrary slack node is set to zero (eq. 7) to ensure the uniqueness of solutions (Egerer et al. 2014).

This application of the ELMOD model uses a simplification of AC load flow to DC load flow model which is an approach commonly found in numerous ELMOD applications. Overbye et al. (2004) discuss the actual differences between the AC and DC flow applications and concludes that the loss of accuracy is very small and that DC results match pretty well AC load flow solutions. To simplify the flow calculations, the ELMOD model follows the work of Schweppe et al. (1988) and Stigler & Todem (2005) where reactive power flows and transmission line's losses are neglected, angle differences are assumed to be small and voltages are standardized to per unit levels (see Purchala et al. (2005) for applicability of these assumptions).

As a result, DC load flow deals only with two variables - voltage angle and active power injections (eq. 8). The net input into a DC line is determined by the line flows of the DC lines multiplied by their factor in the incidence matrix.

4.4. Data description

Our dataset is based on Egerer et al. (2014) in which several adjustments and updates are made. The transmission network system, power plant units and their technical characteristics are completely taken from Egerer et al. (2014) and resemble thus the state of the year 2012. Similarly to the application of Kunz & Zerrahn (2016), the rest of the dataset related to electricity is updated to 2015. Hourly data for load, solar, wind, pump-storage plant generation and pumpstorage plant pumping are obtained from the ENTSOE Transparency platform (ENTSOE 2016) or from the pages of individual TSOs in case of unavailability in the Transparency platform. Prices of electricity to calculate demand are obtained from (European Commission, DG Energy 2016c). Power plant fuels prices are collected from several resources as shown in table 3. Prices of CO_2 allowances are retrieved from the database of European Energy Exchange (EEX) in Leipzig. Data on cross-country price differences in gas and oil are collected from (European Commission, DG Energy 2016d) and (European Commission, DG Energy 2016b), respectively.

4.4.1. Grid

The underlying grid data consist of nodes (transformer stations) which are connected by transmission lines (individual circuits). In several cases, auxiliary nodes are added on the intersection of lines (Egerer et al. 2014). Our dataset consists of 593 nodes, 10 country-specific nodes and 981 lines.

Each transmission line is characterized by several parameters necessary for conduction of a DC load flow model – number of circuits, length, resistance, reactance, voltage level and thermal limit.

There are two levels of detail in our data. First, the transmission systems of Central European countries are reflected to the greatest possible level of detail. This means the structural nature of the network is modelled by taking into account actual lines and substations which are operated by the TSOs. The exact form of the transmission system can be found in Egerer et al. (2014, p.56). It should be stressed though that in contrast to the standard definition of the CE region, in this paper we do not include Hungary. Although the Hungarian TSO participates in many common projects in the region that address the need to deal with loop-flows, the Hungarian transmission system is not primarily affected by them. For this reason, it is not necessary to look at the flows in Hungary in such detailed level as in the other mentioned countries. Thus, in order to simplify computational, we add Hungary to the group of countries where the transmission systems are modelled on a more aggregate level. These countries include all states surrounding the CE region (namely Netherlands, Luxembourg, France, Switzerland, Italy, Slovenia, Hungary, Denmark, and Sweden). Following the work of Leuthold (2009), the networks are aggregated to a country-specific single node which are interconnected with the CE region as well as between each other. The number and properties of interconnectors between the countries are unaffected.

This distinguishes this article from most of the research works which focus primarily on Germany and model only German network in such a detail. Another benefit is that incorporation of aggregated neighbouring states as single nodes prevents severe biases occurring in resulting flows which would be the consequence of absent transit and loop flows of electricity between CE and adjacent areas. The transit flows can be illustrated by the example of Italy, the biggest importer of electricity in Europe. Italy has terrestrial interconnections to France, Switzerland, Austria and Slovenia which supply all the imported electricity. Neglecting this would lead to inappropriate flows in the grid. Nevertheless, the applied model could be extended by at least a Balkan node as discussed in section 4.6.1.

The final dimension of the grid data regards security which the TSO has to take into account. In reality, this is captured by the "N-1" security criterion which is a basic criterion of power system stability. It requires the system to be able to operate and supply electricity provided a sudden outage of one system element occurs (Neuhoff et al. 2005). In the model, this security constraint is introduced by a 20% reliability margin in the thermal limit of each line (Leuthold et al. 2008, p.13).

4.4.2. Generation

Based on the approach in Egerer et al. (2014), generation capacities are divided between “controllable"[2] and variable renewable sources which are treated accordingly. For controllable generation, individual units or power plants are considered separately (only units above 10 MW are considered). Each unit is allocated to one of 20 technological clusters according to the fuel consumed and technology that is utilized by the generation unit. An exact overview and definition can be found in Egerer et al. (2014, p.57). The 607 generation units in the CE region are assigned to specific nodes by the method of shortest distance. In the remaining single node countries, all generation units are summed up over the production technology and allocated to that single node. Due to lack of data availability, all power plants data are taken from Egerer et al. (2014). The disadvantage of this approach is that the generation dataset reflects the state in the year 2012. Thus an assumption about time-invariant development of generation capacities had to be made. The only exception is the German nuclear phase-out which is fully reflected in the dataset for the particular period and scenario. The relaxation of the assumption about time-invariant development and incorporation of the newly built controllable facilities could be a useful future extension of this paper.

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[2] The term controllable includes all generation types that are not dependent on weather conditions and can be controlled by the dispatcher. This includes fossil-based types of sources, nuclear power plants, biomass, waste and non-storage hydro power plants.

Table 7: Efficiency of conventional generation technologies (in %)

	1 950	1960	1970	1980	1990	2000	2010
Nuclear	33	33	33	33	33	33	33
Lignite	29	32	35	38	41	44	47
Coal	29.6	32.8	35.9	39.1	42.3	45.5	48.7
CCGT and CCOT	20	26.7	33.3	40	46.7	53.3	60
Gas Steam and Oil Steam	30.6	33.8	36.9	40.1	43.3	46.5	49.7
OCGT and OCOT	24.7	27.3	29.9	32.5	35.1	37.7	40.3

Source: Egerer et al. (2014, p.70)

Table 8: Availability of conventional generation technologies

Type	Nuclear	Lignite	Coal	CCGT, CCOT	OGCT, OCOT	Gas Steam, Oil Steam	Reservoir, RoR	Hydro
Availability	0.84	0.9	0.87	0.91	0.9	0.89	0.62	0.32

Note: Availability of wind, solar and pump storage power plants is set to one as they enter the model as external parameters. Source: Egerer et al. (2014, p. 70) and Schröder et al. (2013).

Actual generation from individual plants is subject to model optimization after taking the plants' technical parameters into account. These include generation efficiency (tab. 7), availability of production units (tab. 8) and fuel costs.

Fuel costs and emission prices represent the short-term variable costs of producing one MWh. This applies to fossil-based power plants and nuclear power plants, biomass and waste plants whereas hydro, wind and solar plants are considered at zero production cost. For all power plants, other operation and maintenance costs as well as unit commitment costs are not considered (Egerer et al. 2014). Input prices for particular inputs are given in table 9 with the respective data sources. All prices are updated to 2015 values except the price for coal where only 2014 values are available. The price of lignite cannot be found due to the fact that there is no market for lignite. It is thus estimated to be half the price of hard coal. This estimate is based on the calorific value of brown coal as compared to hard coal (9-17 MJ/kg and 19-35 MJ/kg respectively). Bejbl et al. (2014) use a different approach using a model to estimate brown coal price.

Table 9: Fuel prices

Fuel	Price [EUR/MWh$_{th}$], [EUR/t(CO$_2$)]	Source
Uranium	3	Assumption of Egerer et al. (2014)
Lignite	3.48	Own calculation
Hard Coal	6.96	BP: Northwestern Europe coal price 2014
Gas	22.28	EC: Quarterly reports on European gas markets
Oil	28.42	Bloomberg: Brent oil price
Biomass	7.2	Assumption of Egerer et al. (2014)
Hydro	0	
Wind	0	
Sun	0	
Waste	7.2	Assumption of Egerer et al.
Carbon	7.59	EEX: Median CO2 EUA settlement prices

Following Egerer et al. (2014, pp.62, 64) and Leuthold (2009), solar and wind plants are aggregated on nodal basis. This treatment is necessary as both types of power plants are very dispersed and have individually small installed capacity. Incorporation on plant-level basis would thus be infeasible. The result of such aggregation are the weights of specific nodes on total solar or wind production.

Unlike the controllable power plants, water and wind generation enter the model as external parameters for each hour of the week, i.e. the solar and wind generation is not the output of the optimization model. Aggregate data on 2015 hourly generation for the country level are obtained from the ENTSOE transparency platform. Nation-wide production is allocated to individual nodes based on the above-mentioned weights. Lastly, it should be noted that for the reasons of significant computation[3] simplification, pumped-storage hydro power plants are treated in the same manner as wind and solar power plants (as eq. (3) shows).

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[3] As Leuthold et al. (2012) shows, explicit modelling of pumped-storage power plants adds one dimension to the model as the levels of production and consumption (pumping) are interrelated over time. This tremendously increases the computational time and hardware requirements.

4.4.3. Load and electricity price

The ENTSOE database is the source of hourly data for all included countries for the year 2015. The primary need for the load data is the necessity of having a counterpart to the generation on a nodal basis in the CE region and national basis in the rest of countries. However, the load values are available on national level only which is not satisfactory for the purposes of the model. Egerer et al. (2014) suggests using GDP and population as proxies for industrial and residential demand respectively (GDP assumes 60% weight whereas population assumes 40%). All data are taken on the NUTS 3 level, for which the data are available in all cases (Egerer et al. 2014). Exact allocation procedure is described in detail in Egerer et al. (2014) and Leuthold et al. (2012).

Secondary utilization of the load data occurs in the optimization problem where the welfare function is maximized. At each node, the reference demand, reference price and elasticity are estimated in order to identify demand via a linear demand function (Leuthold et al. 2012). Here, as Leuthold suggests, the hourly load is assigned to the nodes according to the node's share described earlier. This, subsequently, yields a reference demand per node. Table 10 shows the prices for relevant countries.

Table 10: Electricity reference prices, [EUR/MWh]

Country	AT	CH	CZ	DE	DK	FR	HU	IT	LU	NL	PL	SI	SK	SE
Price	32.33	36.8	32.53	32.08	25.63	38.75	41.45	53.8	32.08	41.73	41.48	41.93	33.5	18.51

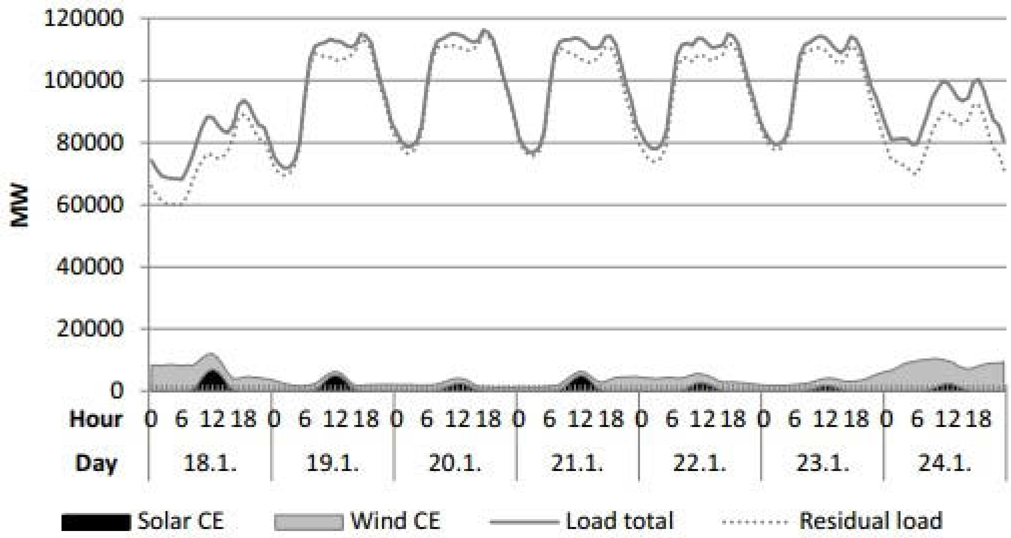
Source: European Commission (2016c)

Demand elasticity is taken as -0.25 based on Green (2007).

4.4.4. Simplification of the full year model

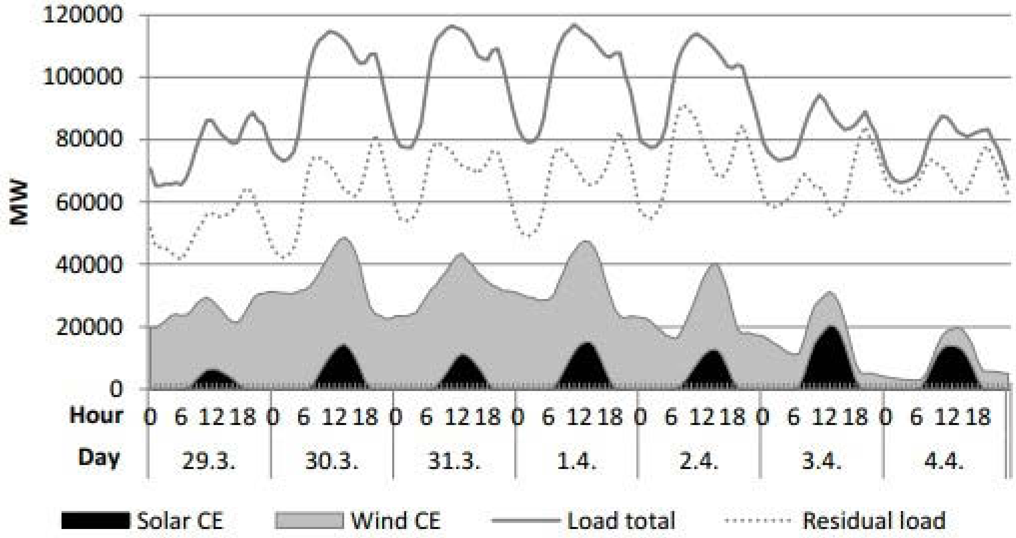
Due to computational limitations resulting from the complex structure of the model, four representative weeks with different combinations of extreme values of RES production are used and investigated in detail. Similarly to Schroeder et al. (2013), four weeks (we use English-type weeks, i.e. the week starts on Sunday) with different values of wind and solar production are chosen. In particular, we speak about two base weeks, week 4 (penultimate week in January - from 18th January to 24th January) and week 14 (last week in March - from 29th March to 4th April), where the cumulative production from wind and sun is lowest or highest in CE, respectively. The two other weeks, 27 (the last week in June from 28th June to 4th July) and 49 (last week in November from 29th November to 5th December), were considered only as a robustness check for our results as they mirror the opposite extremes in production. Thus, week 27 mirrors the situation provided there is a high production from sun and low production from wind and week 49 reflects the opposite. In figures 34 and 35, the aggregate load-generation profiles for CE countries during the base weeks are shown on the real data for 2015. Load, residual load, where Residual load = Load - Sun generation - Wind generation, sun and wind generations are depicted during the respective hours of the week.

Figure 34: Week 4 profile



Source: Own, based on ENTSOE (2016) data

Figure 35: Week 14 profile



Source: Own, based on ENTSOE (2016) data

4.5. Scenarios

To measure exactly the impacts of grid bottlenecks between southern and northern Germany and Energiewende policy on the transmission grid, electricity flows over the individual lines within the network are obtained. Afterwards, they are compared in the context of three scenarios.

The reference scenario, referred to as *base*, models the current situation in the power sector based on the data as specified in section 4.4.

The scenario assesses the full range of impacts of the Energiewende policy in the CE context. It is derived from the base scenario by taking into account the aims of German energy policy for the year 2025. Parameters reflecting VRES production are multiplied by coefficients (table 11), demand is adjusted to reflect the predictions and nuclear power plants are phased-out. Everything else in Germany as well as in the remaining countries, including grids, reflects the state of 2015 or other years as specified in the section 4. From the nature of construction, the results must be read in the context of the worst possible outcome if nothing was to be done in terms of network development.

All relevant electricity-related Energiewende goals are defined as a percentage of electricity consumption as compared to the year 2008. According to AGEB (2015), 618.2 TWh of electricity was consumed in Germany in 2008. Energiewende goals require electricity consumption to be reduced by 10% until 2020 and by 25% until 2050 (BMWi 2015b). Linear approximation leads to a 12.5% reduction in 2025 which accounts for 541 TWh. This comprises 90.61% of the 2015 consumption.

The shares of solar and wind electricity generation are based on the "Netzentwicklungsplan 2025" (Feix et al. 2015) where installed capacities are projected. This document presents scenarios A, B and C. For the purpose of our analysis, scenario "2025 A" is used as it the least ambitious scenario of all three. Firstly, it does not reduce the capacity of the coal power plants so much as scenarios B and C (which is a realistic assumption considering the trends in the German coal power plant sector) and it is also more conservative about the potential amount of RES additions.

The hourly generation of wind and solar plants in 2025 is obtained by multiplying the actual hourly generation in 2015 by coefficients in column (7) in the table 11. This approach yields the renewable/consumption ratio of 45.91%, close to the 42.5% result of linear approximation for the year 2025 using BMWi scenarios (BMWi 2015b). Table 11 summarizes the derivation of the coefficients concisely.

Table 11: Parameters of full scenario model

TYPE	Installed capacity 2013 (MW) (1)	Development coefficient (2)	Installed capacity 2025 (MW) (3)	Full load hours (4)	Generation 2025 (TWh) (5)	Generation 2015 (TWh) (6)	Generation coefficient (7)
Solar	36,340	1.49	54,159.61	969.77	52.52	38.5	**1.364**
Wind onshore	33,310	1.568	52,231.66	1900.46	99.26		
Wind offshore	620	14.355	8900	3118.28	27.75		
Wind	33,930		61,131.66		127.02	86	**1.477**

Source:	Feix et al. (2015)	Feix et al. (2015)	(1)*(2)	data BMWi (2015b)	(3)*(4)	AGEB (2015)	(5)/(6)

Finally, the BMWi scenario was selected because it is highly probable that policy makers will stick to it and will thus follow time-consistent development based on this scenario. This assumption is based on two findings: first, the BMWi scenario exhibits extraordinarily high social acceptance when compared to other development scenarios (Schubert et al. 2015b), and, second, it focuses highly on economic viability and emission reduction (up to 80 % as of 1990 (Keles et al. 2011)) which are both factors playing major role in German public's opinion on Energiewende (Schubert et al. 2015a).

The RES scenario inspects one particular part of the Energiewende policy – the nuclear phase-out or, from the other point of view, the isolated impact of renewables on transmission networks without the nuclear phase-out. It is based on scenario *full*, except the fact that German nuclear power plants are considered to be still in operation even after 2022.

4.6. Results

The results are presented for the two base weeks with low (week 4) and high (week 14) VRES production. There are 30 interconnectors between the countries of Central Europe, 29 interconnectors between the German TSOs, another 39 interconnectors between Central Europe and adjacent states and hundreds of lines within the particular countries. For sake of clarity of results interpretation, the results are reported and interpreted on “border profiles” flows as in Egerer et al. (2014).

There are three kinds of border profiles considered in this paper: border profiles between countries, border profiles between TSOs within Germany, and the border profile between northern and southern Germany. This northern-southern Germany border profile is employed for the examination of the electricity exchanges with respect to the bottlenecks within Germany as described in the section 4.2. This border profile is created similarly to the study of Egerer et al. (2016).

Detailed commentaries are made only for weeks 14 and 4 where peak and trough of cumulative VRES production occurred, respectively. We do not report the results for weeks 27 and 49 as they quantitatively confirm the results for weeks 4 and 14. A brief overview of the results for weeks 27 and 49 can be found in supplementary materials.

Percentage changes in transmission (the sum of absolute values of import and export over the interconnector) and the absolute value of changes of balances (the difference between import and export keeping the flow direction) and transmission are presented together in table 12. The highest relative changes in transmission are on the PL-DE and CZ - 50Hz border profiles in both scenarios *res* and *full* in weeks 14 and 4, respectively. In general, we can observe a higher relative change in transmission compared with the scenario base in week 4 as the absolute levels are lower. On the CZ-PL border profile we can even observe a negative change both in transmission volume and balance direction compared with the scenario base in week 14.

Table 12: Weekly changes compared with the scenario *base*

	Balance ch. [GWh]		Transmission ch. [GWh]		Transmission ch. [%]		Balance ch. [GWh]		Transmission ch. [GWh]		Transmission ch. [%]	
	w4						w14					
Border profile:	res	full	res	full	res	full	res	full	res	full	res	full
CZ-PL	-5.4	-7	9.3	9.3	21.0%	21.1%	-6.5	-7.4	-3	-4.4	-2.7%	-4.1%
CZ-SK	-1.3	-3.1	3.5	4	6.3%	7.3%	-12.6	-18.4	-0.1	4.4	-0.1%	3.7%
CZ-AT	2.3	-1.1	5.4	5.5	5.8%	5.9%	9.1	-0.27	10	1.2	4.7%	0.6%
CZ-50Hz	7.81	7.8	13.6	12.1	39.1%	34.7%	19.5	18.6	18.3	17.4	15.4%	14.6%
CZ-TENNET	-1.6	-3	2	1.7	4.1%	3.5%	-7.1	-11	-4.4	-6.3	-4.6%	-6.5%
PL-DE	21.6	25.4	8.3	10.1	20.1%	24.6%	66.9	65.9	39.8	40.7	45.5%	46.5%
DE-AT	13.6	10.8	16.4	17.3	16.5%	17.3%	72.5	62.3	75	62.87	22.8%	19.2%
PL-SK	-2.8	-3.9	3.4	3.1	18.8%	17.3%	-1.1	-0.5	0.7	0.9	1.3%	1.7%
50Hz-TENNET	19.6	14.62	46	40.5	10.6%	9.3%	4.1	-13.4	118.6	90.8	10.7%	8.2%
TENNET-AMPRION	14.4	4.9	63.5	60.6	14.6%	14.0%	85.2	79.9	84.5	87	7.7%	8.0%
TENNET-TransnetBW	6.4	3.8	12.8	11.4	12.3%	11.0%	27.8	26.4	27.4	26.6	10.6%	10.3%
TransnetBW-AMPRION	3.5	0.3	15.4	15.2	15.4%	15.2%	25.6	28.1	29.3	31	11.7%	12.5%
DE-N-DE-S	0.5	-7.4	53.2	49.4	14.3%	13.3%	-11.6	-14.8	79.4	72.3	8.6%	7.8%

Note: Balance stands for the difference between imports and export of electricity between two zones; Transmission is the total flow over a particular profile i.e. sum of inflows and outflows. Relative change in transmission computed as % of base flow. Change in balance is the (absolute) difference between particular scenario and baseline scenario on specific transmission line; sign "–" signifies that change in imports is bigger than change in exports; sign "+" then the opposite.
Source: Authors.

Table 13 gives then an overview of extreme loads which are defined as a number of occurrences of load at 75% or higher thermal limit of the particular line during the week. By the model's definition, each line is subject to a 20 % margin representing the "N-1" criterion of stability as discussed in section 4, i.e. the permitted flow on every line is 80% of its capacity as in (Leuthold et al. 2008). The 75% capcity criterion is the threshold for treating the flow as critical, because it is near the limit for "N-1" criterion. In week 4 with low VRES feed-in, there is just one occurrence of critical load in the base scenario on the Krajnik-Vierraden line between Poland and Germany. This line also has the highest rate of occurrence of critical loads in week 14 - 13, 46 and 40 in *base*, *res* and *full* scenarios, respectively.

Table 13: Extreme load overview

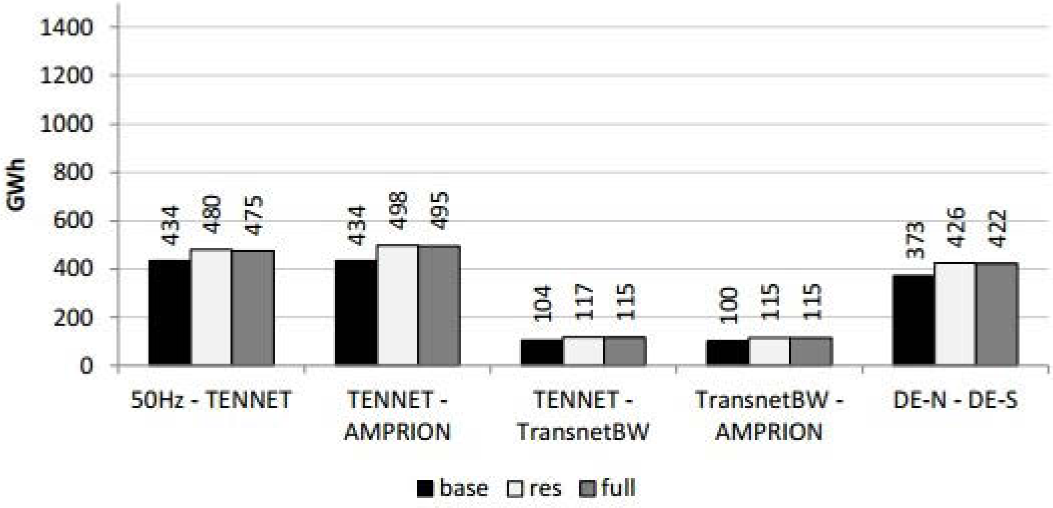
		# extremes					
Interconnector	Substations	w4 base	w4 res	w4 full	w14 base	w14 res	w14 full
PL⇒CZ	Bujakow-Liskovec	-	-	-	-	1	-
CZ⇒PL	Liskovec-Kopanina	-	-	-	-	-	-
PL⇒CZ	Wielopole-Nosovice	-	-	-	-	-	-
CZ⇒PL	Albrechtice-Dobrzen	-	-	-	-	-	-
SK⇒CZ	Varin-Nosovice	-	-	-	-	-	-
CZ⇒AT	Slavetice-Durnrohr	-	-	-	-	-	-
CZ⇒SK	Sokolnice-Stupava	-	-	-	-	-	-
CZ⇒SK	Sokolnice-Krizovany	-	-	-	-	-	-
CZ⇒AT	Sokolnice-Bisamberg	-	-	-	-	-	-
SK⇒CZ	Povazska Bystrica-Liskovec	-	-	-	-	-	-
SK⇒CZ	Senica-sokolnice	-	-	-	-	-	-
CZ⇒Tennet	Hradec II-Etzenricht	-	-	-	-	-	-
CZ⇒50Hertz	Hradec I-Rohrsdorf	-	-	-	-	-	-
CZ⇒Tennet	Prestice-Etzenricht	-	-	-	-	-	-
PL⇒SK	Lemesany-Krosno Iskrzynia	-	-	-	-	-	-
DE⇒AT	Aux-Oberbayern-Burs	-	-	-	-	3	8
DE⇒AT	Vohringen West-Burs	-	-	-	-	-	-
AT⇒DE	Burs-Obermorrweiler	-	-	-	-	-	-
DE⇒AT	Obermorrweiler-Burs	-	-	-	-	-	-
DE⇒AT	Pirach-Sankt Peter	-	-	-	-	-	-
DE⇒AT	Altheim-Sankt Peter	-	-	-	-	-	-
DE⇒AT	Simbach-Sankt Peter	-	-	-	1	3	3
DE⇒AT	Pleinting-Sankt Peter	-	-	-	-	6	3
DE⇒AT	Leupolz-Westtirol	-	-	-	-	-	-
DE⇒AT	Leupolz-Westtirol	-	-	-	-	-	-
AT⇒DE	Burs-Grunkraut	-	-	-	-	-	-
DE⇒AT	Pleinting-Sankt Peter	-	-	-	-	6	3
AT⇒DE	Sankt Peter-Pirach	-	-	-	-	-	-
PL⇒DE	Mikulowa-Neuerbau	-	-	-	-	1	3
PL⇒DE	Krajnik-Vierraden	1	-	-	13	46	40

Note: The values represent the number of hours with extreme load occurrence in given week; each week works with 168 h. For instance, the interpretation of line Krajnik-Viarraden in week's 14 res scenario is that the line experiences extreme load during 27.4% of time.
Source: Authors.

4.6.1. Week 4 - low VRES production

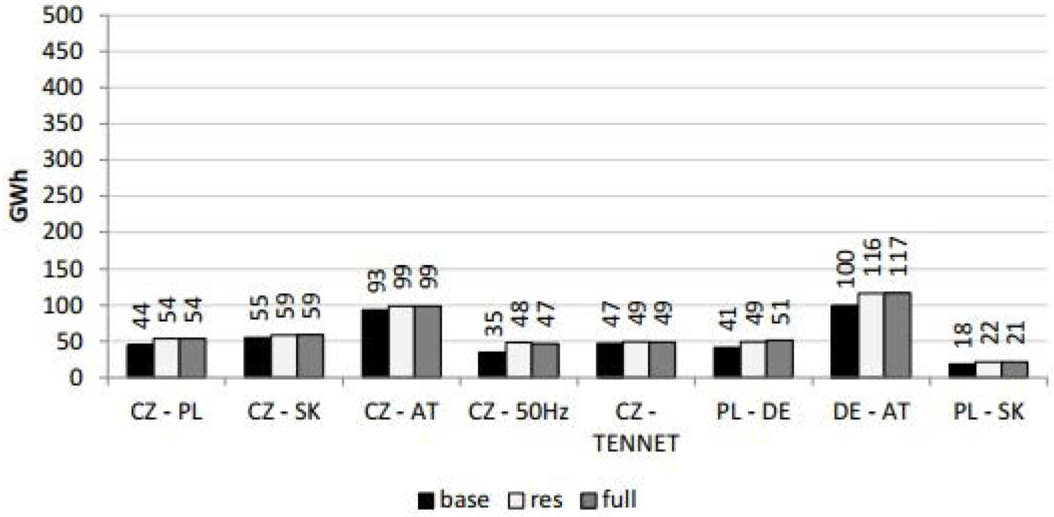
The general effect of low VRES production is the low international balance as well as total transmission of electricity (fig. 7 - 8).

Figure 36: Transmission DE, W4



The base scenario results for exchange balance fit those actually observed, except in the case of Czech-Slovak and Polish-German borders. Despite this fact, week 4 results exhibit quite a poor performance in amount predictions. Reversed flow on the Czech-Slovak border is structural in the model due to the fact that electricity flows from the Czech Republic through Slovakia to Hungary and further to Balkan countries in is actually the case in reality. In the model, the Balkan countries are not modelled with the above-mentioned consequence. The problem could be solved in the future by combining Balkan countries as one additional importing node.

Figure 37: Transmission CE, W4



The poor performance of the model's prediction in this particular week with low load might be linked to the single TSO's area nature of the model. As a low share of zeromarginal cost renewable production enters the model, non-zero cost conventional production must occure in order to meet the demand. Because of the single TSO in the model, the whole area is optimized at once. Therefore, conventional power plants produce at the most local level as possible and the necessity for cross-zonal transport of electricity is limited. Furthermore, the similar predictive power of the model was found in other studies, e.g. in Egerer et al. (2014).

Comparison of the scenarios *res* and *full* does not confirm the anticipated negative impacts on the grid of nuclear phase-out in the sense of exacerbating the overloading of grids in the north-south direction in Germany and in sense of greater loop flows through Poland and the Czech Republic (table 6, Figures 36 and 37). The average utilization of cross border-interconnectors is very low (below 20 %) as a result of the low amount of transport as explained above. Even though some increase of utilization can be observed on all but three lines, the increase is very modest. A maximal rise of 6,56% is measured over the Krajnik (PL)-Vierraden (DE) line.

The results also confirm that VRES induce growth of volatility of transmission and, consequently, contribute to system destabilization. All but three lines evince standard deviation increment and thus more fluctuating flows can be observed. Unlike in the previous case with the average load, the degree of volatility differs between res and full scenarios. In both cases, the higher degree of volatility can be observed, but nuclear phase-out in the full scenario further aggravates it.

Within the scope of week 4, only one critical event, when the flow on the particular line exceeds 75% thermal limit of the line, occurs on the Krajnik-Vierraden line (table 7). This is due to the fact that the general load is very low in this week.

4.6.2. Week 14 - high VRES production

The qualitative nature of the results for this week is essentially the same as for week 4. Nevertheless, the magnitudes and strengths of effects are notably larger. Actual total transmission average rose 2.54 times, maximal relative one increased about 3.41 times (CZ-Tennet profile) and maximal absolute one grew by 670.3 GWh (50Hz -Tennet profile).

Figure 38: Transmission DE, W14

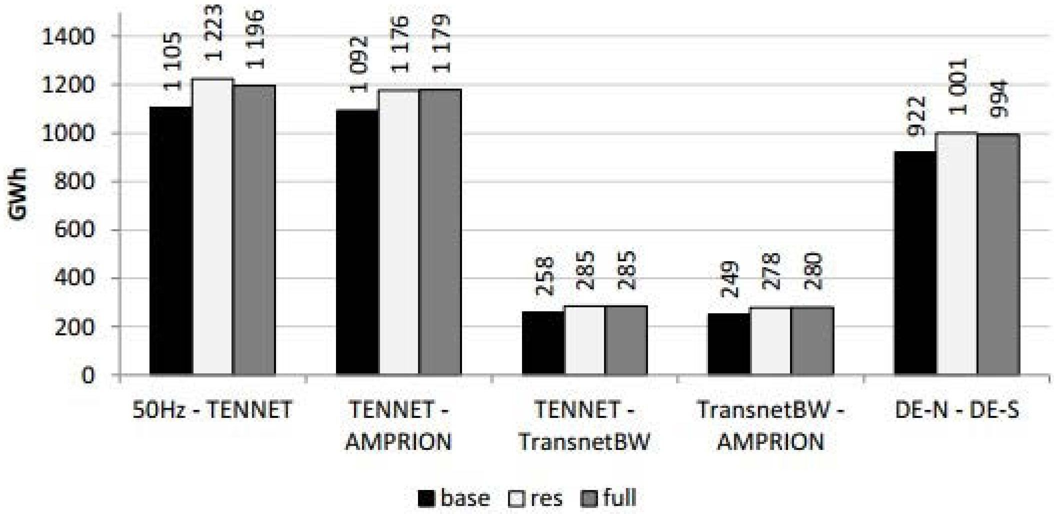
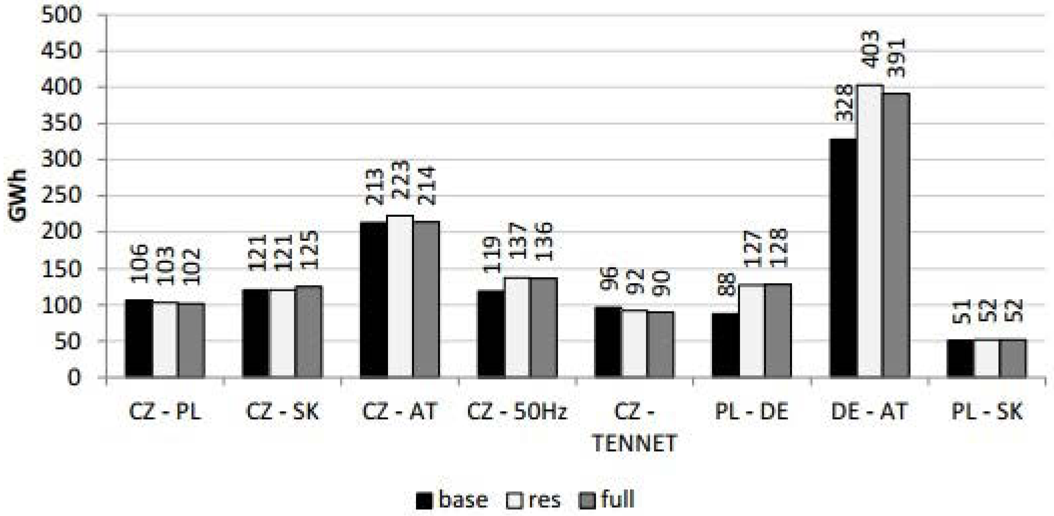


Figure 39: Transmission CE, W14



Scenarios res and full yield both higher exchanges and larger amounts of transmitted electricity as compared to base but again the influence of nuclear phase-out, i.e. the difference between res and full flows, is counter-intuitive. Flows in the full scenario are actually almost the same or lower than in the case of *res* but they were originally expected to be much higher. It is very likely that the answer to this question is hidden in the merit order effect. When base-load and cheaply operating nuclear power plants are shut down, the electricity supply curve shifts to the left resulting in a higher price.[4] This incentivizes more flexible but more costly hard-coal, gas or even oil power plants to produce and supply electricity locally and flexibly to smooth the volatile VRES production. These amounts are not enough to equilibrate all the increase in volatile production but they can significantly ammeliorate it. The exact effect of the smoothing (and consequently the amount of electricity transport) depends on the magnitude of the merit order shift and on the increase of the production from the conventional power units. These merit order price-related effects are not exactly measured in this paper as they require a completely independent research question.

Within the scope of week 14, a roughly 10% increase occurs on profiles in Germany (Figure 38) in RES and full scenarios compared to the base scenario. The other profiles exhibit various behaviour, ranging from slight decreases to immense growths (Figure. 39). German-Austrian and German-Polish border profiles face 46.5 % and 19.2% transmission increases, respectively, when the full scenario is considered. Also the average load on particular lines on these profiles rose (as much as 18.2%, in the case of the Krajnik-Vierraden line). Intuitively, this is also accompanied by the upturn in critical events growing cumulatively by 16 on all 13 DE-AT lines and by 27 on only two 50Hz-PL lines as compared to the base situation (table 7).

Growth of standard deviation can be observed on the base-res basis as well as on the base-full basis on all but two border lines. Also the res-full comparison shows a rise in volatility on the majority of lines. In all three cases, particularly interconnectors between Germany and Austria are under the biggest volatility pressure; the highest values attain a 50% increase.

4.6.3. North-Western Europe

Despite the fact that North-Western Europe is not the area of our particular interest, it is very important to mention that the impact of the above mentioned high VRES feed-in combined with the scenarios have a much more striking impact on this area than on the CE area, especially in week 14 (fig. 8). Whilst the increases in flows of electrical current are still in manageable terms in CE, different effects can be measured on the borders of Germany and Netherlands and

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[4] Exogenously assumed marginal cost production cost of electricity [€/Mwh] for individual technology are following: Nuclear 9.1, Lignite, 6.9, Coal 23.1, CCGT 43.9, OCGT, 70.0, GasSteam 61.1, CCOT 61.1, OCOT 89.80, OilSteam 78.3, Waste 7.2, Biomass 7.2. *The marginal cost are calculated based on exogenously assumed fuel cost, efficiency, corbon content of fuel and price of CO2.*

Germany and France, for example. In the former case, the lines are hitting their limits almost continuously. Altogether 4 interconnectors connect Netherlands and Germany. These lines are subject to a very high average load ranging from 57% to 75.5%. Also, 257 critical events occurred in the base scenario which increased by another approximately 49 events when full scenario is considered. A slightly better situation can be seen in the latter case of the German-French border. These amounts represent absolutely critical values for system manageability and stability.

4.7. Conclusion

The overall novelty of this paper lies in the enrichment of current literature on transmission networks in Central Europe which is generally very sparse. According to our knowledge, this paper is the first to conduct a detailed load flow analysis for the CE region using the ELMOD model, in which the same degree of grid detail was modelled not only for Germany but also for the remaining CE countries. Additionally, the result that nuclear phase-out does not exacerbate grid overload is of great importance as it goes against widely accepted conventional knowledge.

The paper thoroughly examined power and transmission systems in Central Europe. Three key issues were identified: i) the capacity of the grid in Germany does not correspond to the needs emerging from the Energiewende policy which creates grid bottlenecks between northern and southern Germany, ii) this induces the electricity to flow through the energy systems of neighbouring states and iii) current market design in the form of the German-Austrian bidding zone further exacerbates the problems.

Our analysis revealed several important findings. First of all, the higher the feed-in of solar and wind power plants, the higher is the exchange balance and total transport of electricity between TSO areas. This holds for international cross-border profiles as well as for intra-Germany ones. The rise in flows leads also to an increase in the number of critical events which directly endanger grid stability. Furthermore, the model results fit the real values much better under the peak VRES production. This is an important feature of the model as the high amounts of volatile inflows are of substantial importance when examining transmission grids. Additional analysis found that while the situation remains manageable in CE, North-Western Europe should be concerned about this issue to an even greater degree.

Two scenario developments, full and res, were examined. The first attempted to measure the ceteris paribus effect of German Energiewende on transmission networks, especially in the context of CE. The latter scenario excluded nuclear phase-out and thus assessed the isolated ceteris paribus impact of increased solar and wind power production.

In the case of res, all expectations were met. The amount of cross-border transmission grew both on intra-national lines as well as on the cross-zonal ones; so did the average load on majority of particular lines. Moreover, a significant rise in volatility of flows was observed.

Our case of full scenario revealed that nuclear phase-out does not significantly contribute to the amount of transmission as well as to the average load on lines; instead, these remain almost unchanged or slightly decrease. The reasoning for this behaviour lies presumably in the merit order effect. On the other hand, our results suggest that volatility grows as nuclear plants are shut down. This is in accordance with intuition as the nuclear power plants supply stable base-load output.

Finally, focusing on separate peaks in solar and wind production showed that the combination of high solar and low wind feed-in induces greater volatility and cross-border flows on the Czech-Austrian and German-Austrian borders. This finding is critical as it is predicted that solar power will be economically viable without subsidies within a 30 years horizon (Torani et al. 2016). A sky-rocketing increase in installed capacity can thus be expected.

On the contrary, low solar and high wind production leads to the highest observed flows within Germany as well as on transnational lines, except on the German-Austrian border. Thus, the electricity loop flows through other CE countries take up on intensity.

Our results also indicate new questions for further research. One direction entails the relaxation of the ceteris paribus assumption and explicit incorporation of network expansion, decommissioning of controllable capacities as well as the connection of newly built power plants across the whole region that would allow the inclusion of externalities in terms of the social cost of carbon (Havránek et al. 2015) and damage from air pollutants (Máca et al. 2012) into the analysis. Also, the nodal character of the model could be replaced by zonal definition, which would lead to closer reflection of existing design of the market. This would allow closer inspection of cross-border congestion management, cooperation in cross-border infrastructure development etc. Finally, the exogenously given welfare-maximizing social planner could be replaced by endogenous political institutions.

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5. Conclusions

The objective of this dissertation is to contribute to the better understanding of interlinkages between the energy system, the economy and environmental burden. First, we analyse the drivers of reduction in air pollutants emissions stemming from large stationary emission sources in the Czech Republic from 1990 to 2016. This *ex post* analysis helps us to understand underlying factors of enormous air quality emission reduction, considering the institutional and economic context. Then, we move to *ex ante* analysis and address market at which energy is generated and examine in particular the economic factors that determined volume of emissions stemming from the energy generation. We pay a special attention to emission regulation and the impacts that this regulation may induce in the energy system, including the effects on CO2 and air pollutants emissions and associated external costs. Finally, we focus on technical detail of energy market and analyse the impacts of increasing share of power generation from intermittent wind and solar power plants on transmission networks in the Czech Republic, and also on its neighbouring countries (Austria, Germany, Poland and Slovakia).

Chapter 2 analyses the main driving forces of significant reduction in air quality pollutants emitted by large stationary emissions sources in the Czech Republic from 1990 to 2016. We use Logarithmic Mean Divisia Index decomposition (Ang & Liu, 2001) and statistically decompose annual changes in the emissions of four types of air quality pollutants –SO_2, NOx, CO and particulate matters– over the period 1990–2016. While most of previous decomposition studies have been decomposing emissions into scale, structure and emission intensity factors, a unique environmental dataset allows us to further decompose the emission per output effect into [i] the emission-fuel factor, [ii] the fuel-mix factor, and [iii] the fuel-intensity factor, yielding a 5-factor decomposition. The largest drop in emission of all four pollutants occurred from 1990 to 1999 when the emissions decreased cumulatively by 74 % at least. In this period, the firms faced new competitive environment and new command and control regulation – as a result, negative emission-fuel intensity effect was the key driver of emission reduction. However, the fuel intensity effect (fuel use per Euro value added) contributed most to reduction of SO_2, NOx and PM emission in the first 3 years after 1989. Since 2008, activity, structure, fuel-intensity and emission-fuel factors have contributed to emissions changes in similar magnitude, but mainly activity and fuel-intensity in positive directions. In 2015 and 2016, the emission-fuel factor became important again, as the large stationary emission sources had to comply with new strict emission limits set by the Directive on industrial emissions 2010/75/EU. Since data are available in finer sectoral breakdown from the year 1995 only, we perform a sensitivity analysis on LMDI decomposition using data with various sectoral breakdown. Moreover, we perform a sensitivity analysis to decompose emissions into 3-, 4-, and 5-factors to document advantage of our study compared to standard approach that has been relying on a 3-factors decomposition.

Chapter 3 summarizes my research on energy system optimisation. In order to analyse the impacts of regulation, fuel price changes or deployment of advanced or controversial technologies on the energy system, a partial equilibrium least-cost optimisation energy system model TIMES has been built for the Czech Republic. Since technology scenario and modelling impacts cover the period up to 2050, this model has been applied to assess the impacts of several recently discussed policies, including the impacts of deep decarbonisation. The presented chapter specifically reacts on the decision of the Czech governmental to lift brown coal mining limits in the Northern Bohemia coal basin introduced in 2015 (*"Prolomení územních ekologických limitů těžby hnědého uhlí"*). The paper analyses the impacts of maintaining the ban on mining coal reserves and compare them with three alternative options to lift the ban, as discussed by the Czech government. The impacts of each of these alternative governmental propositions are analysed on the fuel- and the technology-mix, the investment, operational and fuel costs of generating energy, related emissions and the external costs associated with these emissions. We find that overall the effect of lifting the ban on coal usage, air pollutant emissions and externalities is rather small, up to 1–2% compared to the level of keeping the ban. The environmental and external health costs attributable to emissions of local air pollutants stemming from power generation are in a range of €26–32 billion over the whole period. The impacts of the three proposed policy options to lift the ban do not differ much compared to the pre-2015 policy that would keep the ban. The small differences in the impacts of the counter-factual scenarios hold even if we assume different prices of fossil fuels costs of the European Emission Allowances to emit carbon emissions, or deployment of new nuclear power technology in the energy system. Contrary, changing these model input assumptions results in larger differences in the impacts than the four policy options do. With respect to the European Energy Roadmap 2050 targets even the most stringent policy scenario (i.e. maintaining the ban) would not result in achieving the 80% carbon emission reduction target. The newly adopted lifting of brown coal mining limits in 2015 would miss this target to an even greater degree.

Chapter 4 addresses more the technical detail of energy system and expand its geographical focus to the Central Europe. We analyse the impact of massive increase in wind and solar installations in Germany on transmission networks in whole Central Europe. Our research performs *ex-ante* analysis of the electricity loop-flows in the Central European countries that has not been analysed yet. Specifically, we examine effect of German policy "*Energiewende"* that contributed, together with insufficient transmission capacity between the northern and the southern part of Germany and the German-Austrian bidding zone, to congestion in the Central European transmission system. To assess this impact on relevant transmission grid, the direct current load flow optimisation model ELMOD is built and then employed for the impact assessment. Impacts of two scenarios for the year 2025 are evaluated on the basis of four representative weeks. The first scenario focuses on the effect of *Energiewende* on the transmission networks, while the second scenario assesses isolated effect of increased feed-in of renewable energy when nuclear power plants are phase-out. Our analysis indicates that higher feed-in of solar and wind power increases the exchange balance, total transport of electricity between transmission system operator areas and average load of lines. Volatility of electricity flows is also increased and solar power is a key contributor to this increase, while wind power is a key loop-flow contributor. Nuclear power phase-out in Germany does not exacerbate these problems.

There are several challenges the Czech energy market will have to face to. Regulation of carbon and air quality pollutants and deployment of nuclear power will be certainly playing the key role in the market development. We have examined possible effects of each of these factors in our research. There are still other issues that will be also playing their important role in the EU energy market that have not been adequately addressed in our models. These include regulation of carbon emissions from non-ETS sectors, reducing air quality concentration, or residential heating that is heavily supplied from district heating. Our future modelling will therefore address the effect of expected increases in EUA and natural gas price on price of heat supplied from district heating and consequently what impacts may induce this pricing effect on whole Czech energy market. Clean mobility and in particular replacement of conventional vehicles by battery electric vehicles is our next research agenda.

Appendices

Appendix A to chapter 2

Four factor decomposition for 26 sector aggregation from 1990 to 2016

Figure 1 4-factor decomposition of SO2 emission from 1990 to 2016

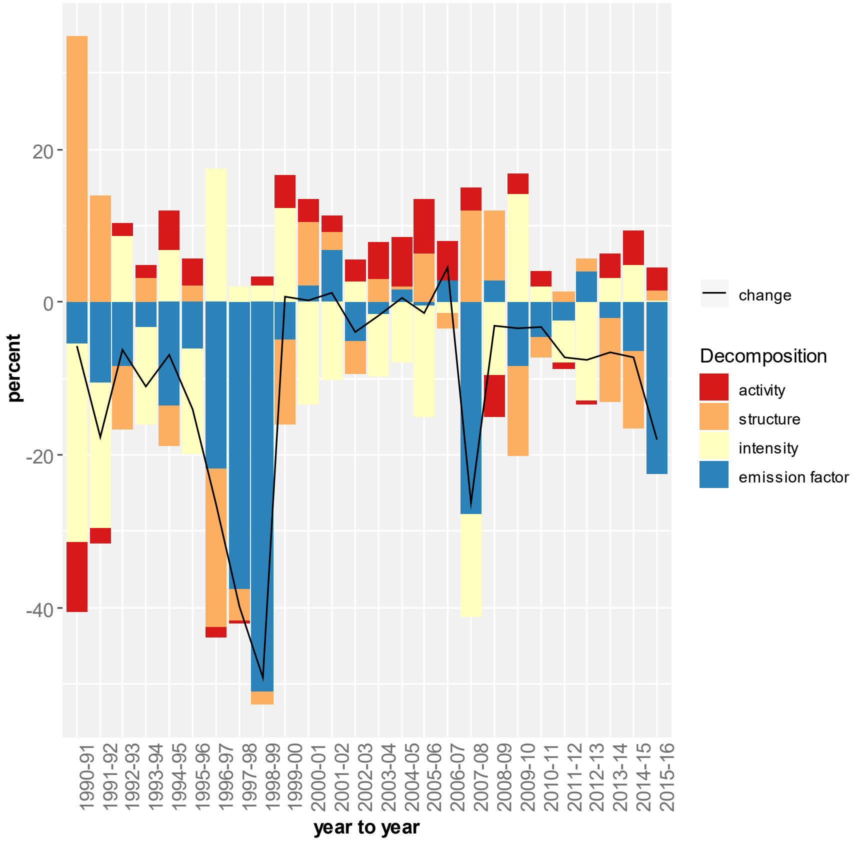


Figure 2 4-factor decomposition of NOx emission from 1990 to 2016

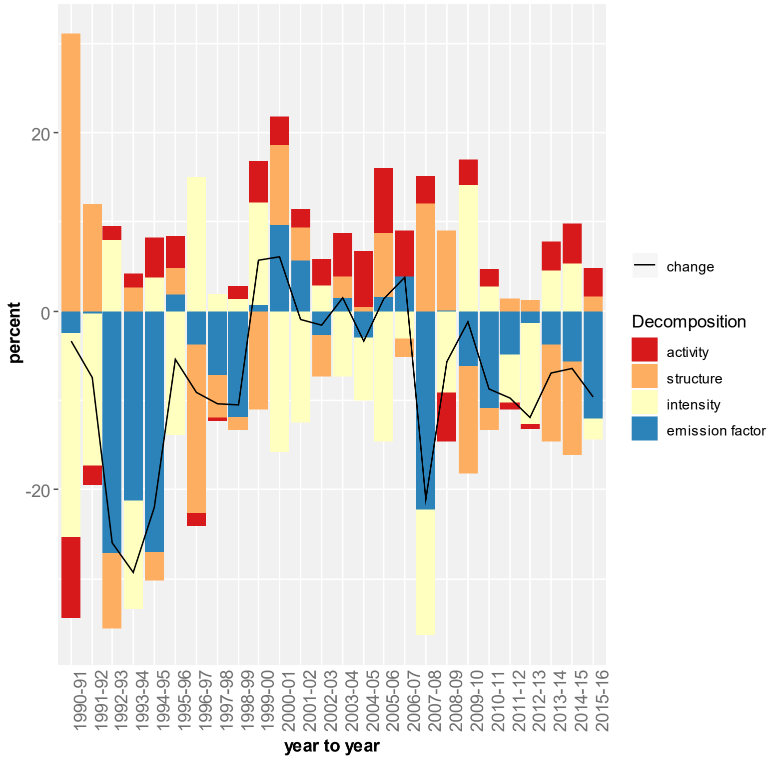


Figure 3 4-factor decomposition of CO emission from 1990 to 2016

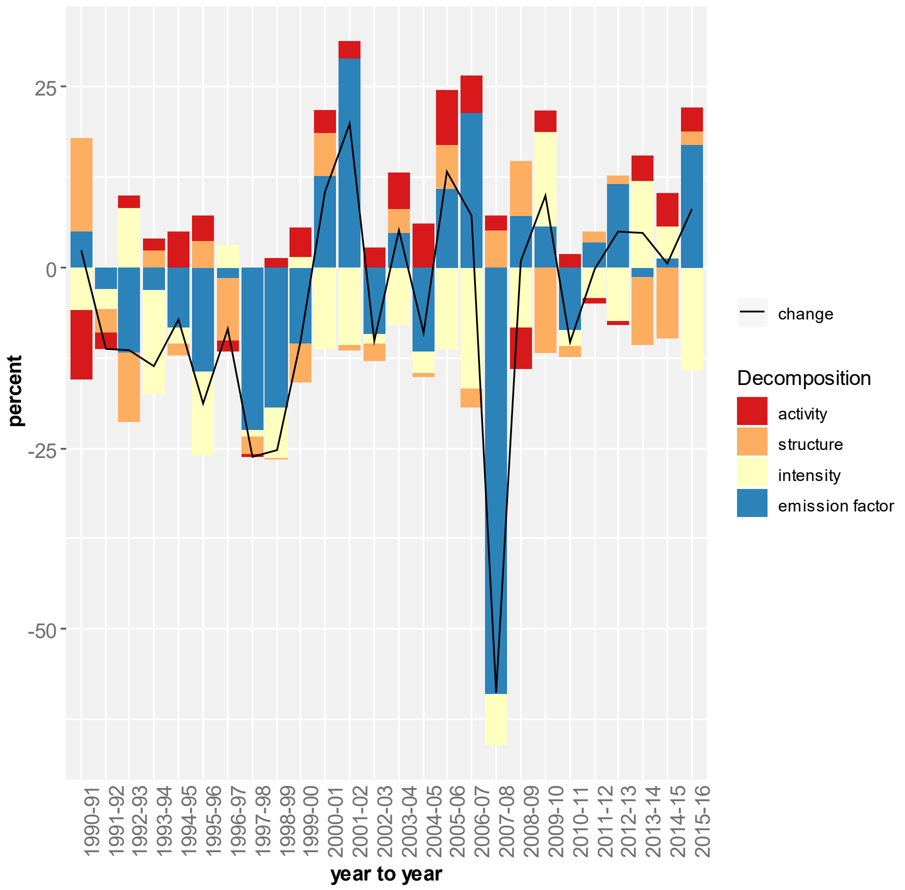
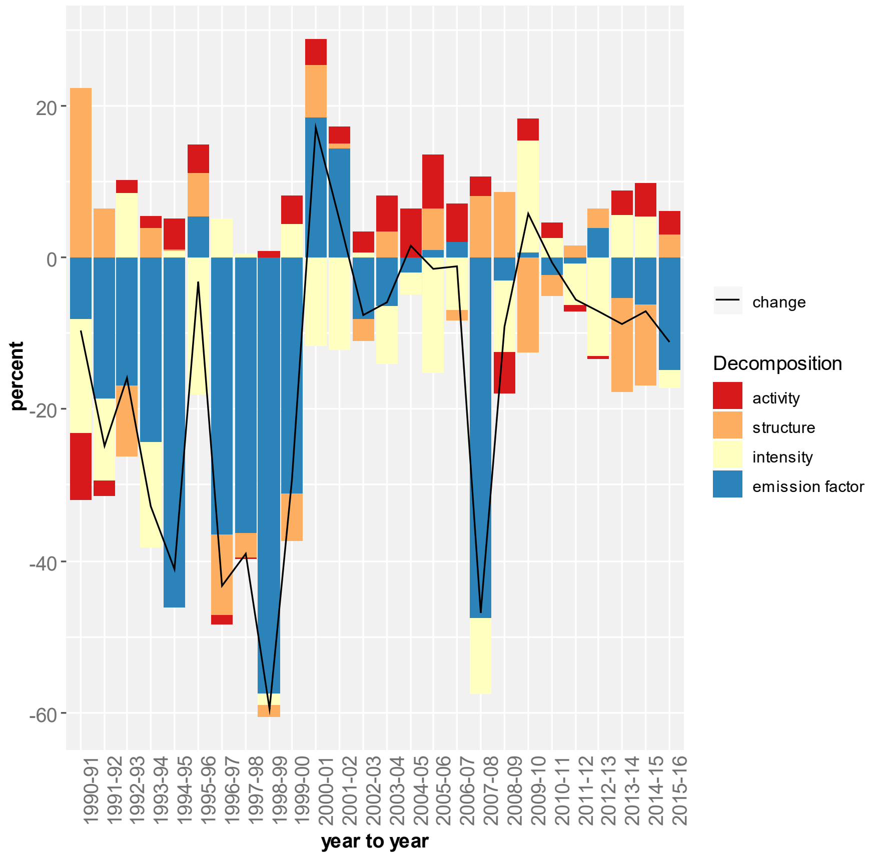


Figure 4 4-factor decomposition of PM emission from 1990 to 2016



Five factor decomposition for 44 sector aggregation from 1995 to 2016

Figure 5 5 factor decomposition of SO2 emission from 1995 to 2016

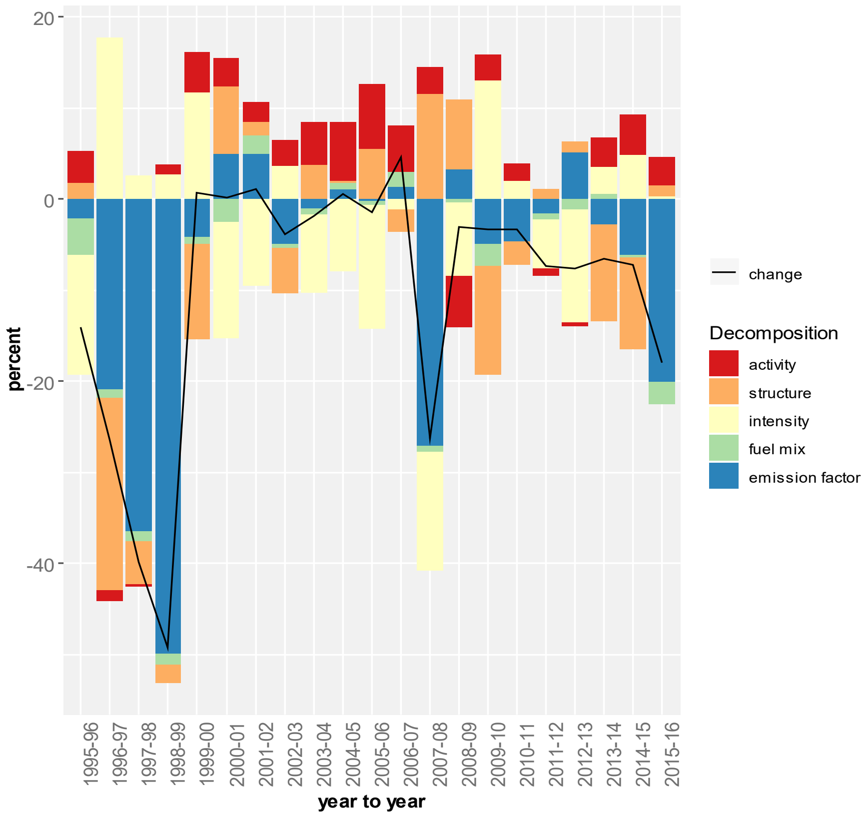


Figure 6 5 factor decomposition of NOx emission from 1995 to 2016

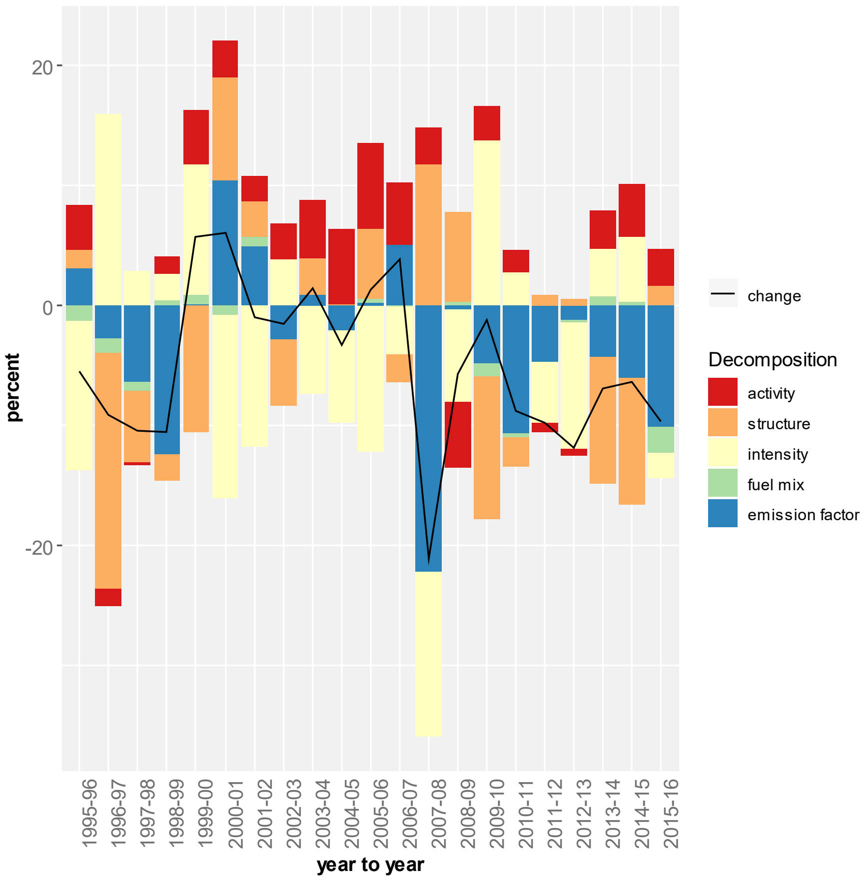


Figure 7 5-factor decomposition of CO emission from 1995 to 2016

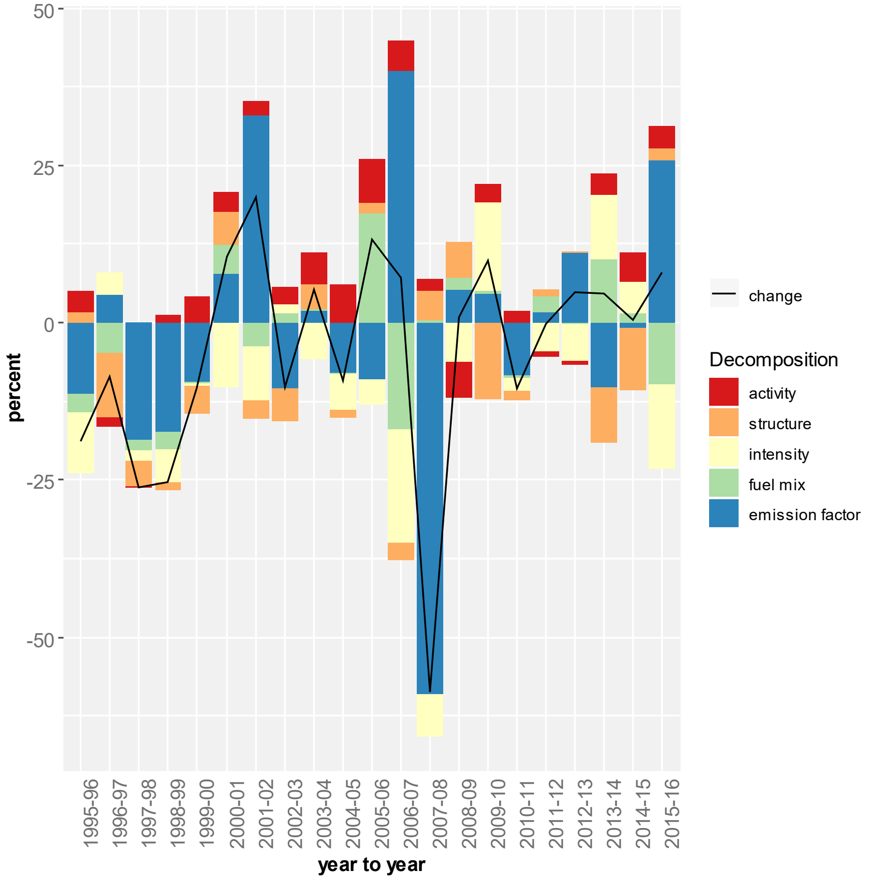


Figure 8 5-factor decomposition of PM emission from 1995 to 2016

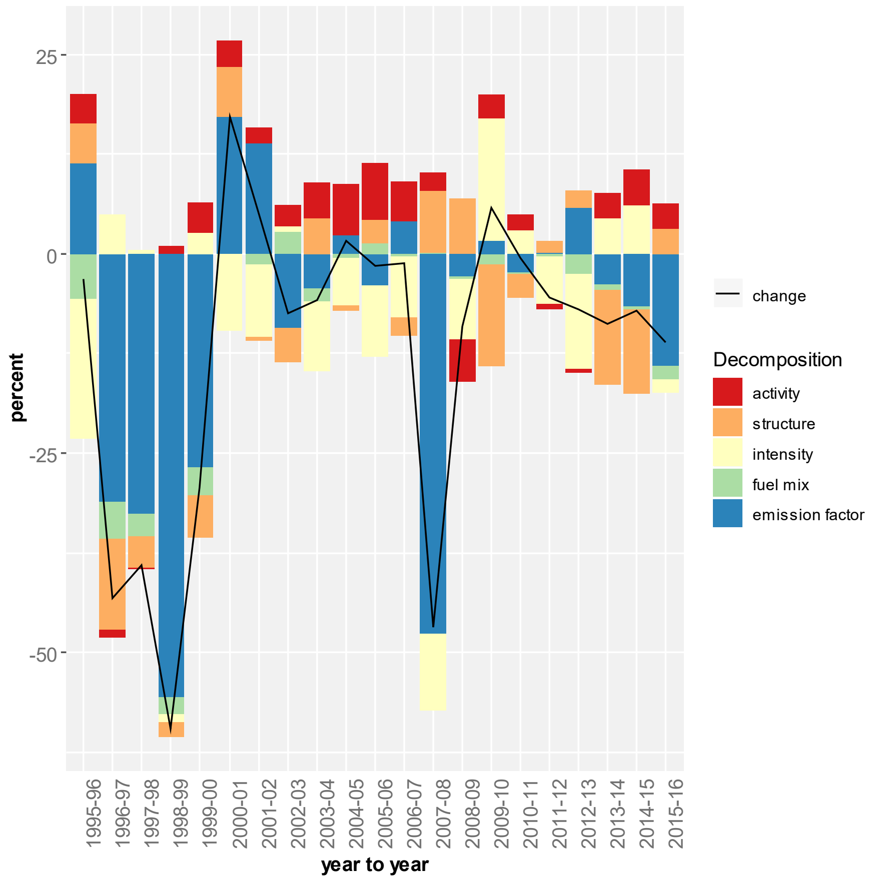


Table 1 5-factor decompostion for selected periods – first and last years

Pollutant	Period	Change (kt)	Change	Activity	Structure	Intensity	Fuel mix	Em. factor
CO	1990-99	-68.2	-74%	0.4%	1.8%	-27.4%	-15.0%	-33.6%
	1999-07	5.7	23%	36.9%	4.4%	-61.8%	4.2%	39.7%
	2008-16	3.9	29%	9.9%	-18.4%	-12.3%	4.6%	45.6%
NOx	1990-99	-358.5	-75%	0.4%	6.2%	-18.9%	-4.0%	-58.5%
	1999-07	15.0	12%	37.5%	4.9%	-48.8%	0.0%	18.9%
	2008-16	-52.2	-47%	6.6%	-15.3%	-3.6%	-2.5%	-32.2%
PM	1990-99	-369.3	-97%	0.2%	1.8%	-11.1%	-8.3%	-79.6%
	1999-07	-3.0	-26%	29.3%	3.1%	-42.8%	1.6%	-16.8%
	2008-16	-1.8	-38%	7.0%	-15.7%	-3.7%	-5.2%	-20.3%
SO2	1990-99	-1391.4	-88%	0.3%	5.2%	-14.1%	-6.5%	-73.3%
	1999-07	-1.0	-1%	34.7%	3.0%	-40.5%	1.2%	0.9%
	2008-16	-60.6	-45%	6.7%	-15.7%	-3.4%	-6.8%	-25.8%

Note: The change from 2007 to 2008 is not included in the cumulative decomposition due to the data inconsistency between years 2007 and 2008, described in section **Error! Reference source not found.**.

Table 2 5-factor decompostion for selected periods – sums over years in periods

Pollutant	Period	Change (kt)	Change	Activity	Structure	Intensity	Fuel mix	Em. factor
CO	1990-99	-68.2	-74%	-3.6%	-1.2%	-23.7%	-13.0%	-32.3%
	1999-07	-10.8	-45%	39.9%	8.4%	-69.2%	2.3%	-26.1%
	2008-16	3.9	29%	11.5%	-18.2%	-16.5%	7.1%	45.4%
NOx	1990-99	-358.5	-75%	-5.6%	28.2%	-37.4%	-2.1%	-57.9%
	1999-07	15.0	12%	39.0%	6.0%	-49.8%	0.9%	16.5%
	2008-16	-52.2	-47%	4.7%	-15.0%	-2.7%	-2.1%	-31.9%
PM	1990-99	-369.3	-97%	-6.5%	22.9%	-29.6%	-6.4%	-77.3%
	1999-07	-3.0	-26%	27.9%	2.1%	-37.2%	-2.2%	-16.1%
	2008-16	-1.8	-38%	6.2%	-17.5%	-3.9%	-5.7%	-16.9%
So2	1990-99	-1391.4	-88%	-3.6%	29.3%	-40.1%	-8.2%	-65.8%
	1999-07	-1.0	-1%	35.1%	2.6%	-39.3%	-0.3%	1.4%
	2008-16	-60.6	-45%	5.6%	-17.1%	-3.3%	-7.1%	-23.0%

Table 3 Aggregation of sectors

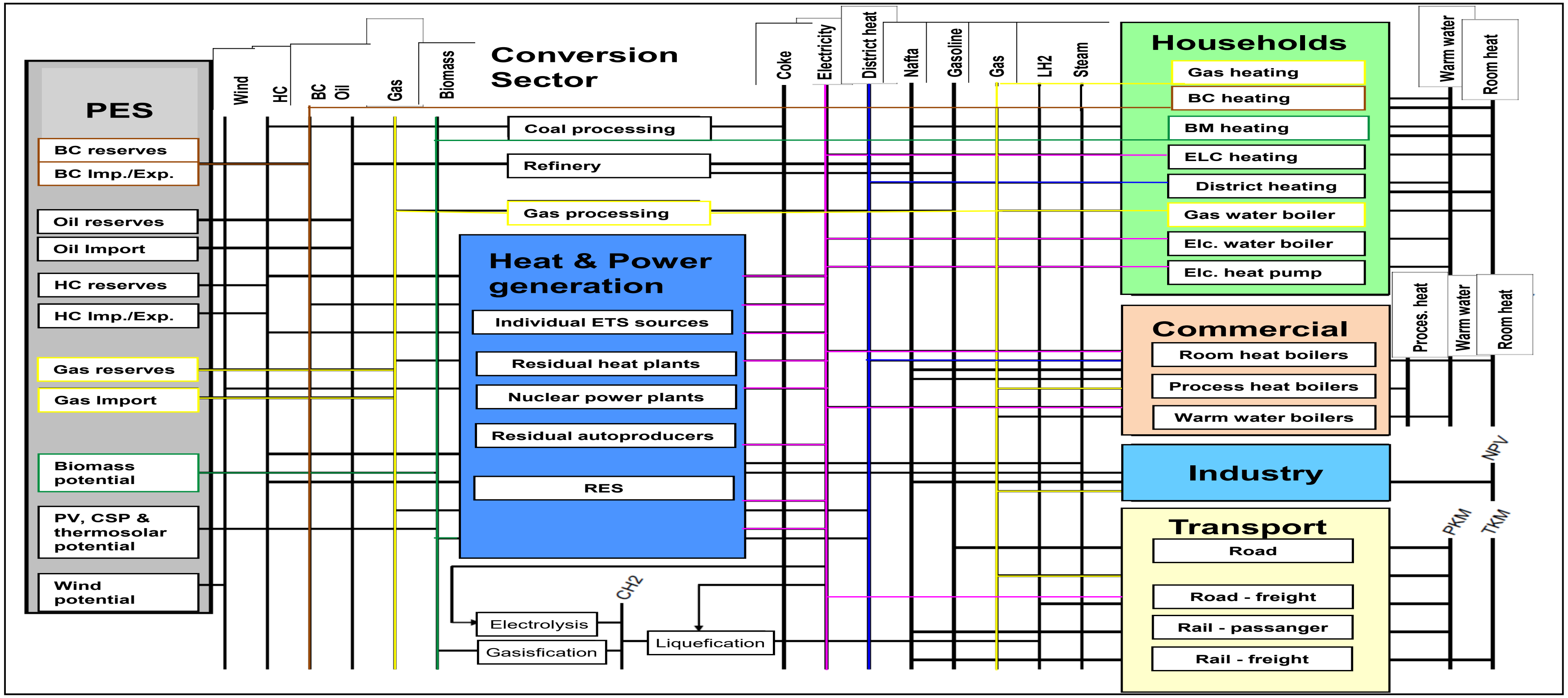
Sec (18)	Simple NACE rev.2	**Simple_Str (26)**	**NACE2 agregation (44)**	NACE rev.2	Description - NACE rev.2 (adjusted)
A	A	A	A	01	Agriculture
A	A	A	A	02	Forestry and logging
A	A	A	A	03	Fishing and aquaculture
B	B	B	05	05	Mining of coal and lignite
B	B	B	06	06	Extraction of crude petroleum and natural gas
B	B	B	07	07	Mining of metal ores
B	B	B	08	08	Other mining and quarrying
B	B	B	09	09	Mining support service activities
C,J,K	CA	CA	10	10	Food products
C,J,K	CA	CA	11	11	Beverages
C,J,K	CA	CA	12	12	Tobacco products
C,J,K	CB	CB	13	13	Textiles
C,J,K	CB	CB	14	14	Wearing apparel
C,J,K	CB	CB	15	15	Leather and related products
C,J,K	CC	CC,JK	16	16	Wood and of products of wood , except furnitur
C,J,K	CC	CC,JK	17	17	Paper and paper products
C,J,K	CC	CC,JK	18,J,K	18	Printing and reproduction of recorded media
C,J,K	CD	CD	19	19	Coke and refined petroleum products
C,J,K	CE	CE	20	20	Chemicals and chemical products
C,J,K	CF	CF	21	21	Pharmaceutical products and preparations
C,J,K	CG	CG	22	22	Rubber and plastic products
C,J,K	CG	CG	23	23	Non-metallic mineral products
C,J,K	CH	CH-CM	24	24	Basic metals
C,J,K	CH	CH-CM	25, 28-30, 33	25	Fabricated metal products, except machinery
C,J,K	CI	CH-CM	26-27,32	26	Computer, electronic and optical products
C,J,K	CJ	CH-CM	26-27,32	27	Electrical equipment
C,J,K	CK	CH-CM	25, 28-30, 33	28	Machinery and equipment n.e.c.
C,J,K	CL	CH-CM	25, 28-30, 33	29	Motor vehicles, trailers and semi-trailers
C,J,K	CL	CH-CM	25, 28-30, 33	30	Other transport equipment
C,J,K	CM	CH-CM	31	31	Furniture
C,J,K	CM	CH-CM	26-27,32	32	Other manufacturing
C,J,K	CM	CH-CM	25, 28-30, 33	33	Repair and installation of machinery
D	D	D	35	35	Electricity, heat and gas
E	E	E	36	36	Water collection, treatment and supply
E	E	E	37-39	37	Sewerage
E	E	E	37-39	38	Waste collection, treatment; materials recovery
E	E	E	37-39	39	Remediation activities
F	F	F	F	41	Construction of buildings
F	F	F	F	42	Civil engineering

F	F	F	F	43	Specialised construction activities
G	G	G	G	45	Wholesale and retail trade
G	G	G	G	46	Wholesale trade, except of motor vehicles and motorcycles
G	G	G	G	47	Retail trade, except of motor vehicles and motorcycles
H	H	H	H	49	Land transport and transport via pipelines
H	H	H	H	50	Water transport
H	H	H	H	51	Air transport
H	H	H	H	52	Warehousing and support activities for transportation
H	H	H	H	53	Postal and courier activities
I,L	I	I,L	I,68	55	Accommodation
I,L	I	I,L	I,68	56	Food and beverage service activities
C,J,K	JA	CC,JK	18,J,K	58	Publishing activities
C,J,K	JA	CC,JK	18,J,K	59	Motion picture, video and television programme production, sound recording and music publishir activities
C,J,K	JA	CC,JK	18,J,K	60	Programming and broadcasting activities
C,J,K	JB	CC,JK	18,J,K	61	Telecommunications
C,J,K	JC	CC,JK	18,J,K	62	Computer programming, consultancy and relatec activities
C,J,K	JC	CC,JK	18,J,K	63	Information service activities
C,J,K	K	CC,JK	18,J,K	64	Financial service activities, except insurance anc pension funding
C,J,K	K	CC,JK	18,J,K	65	Insurance, reinsurance and pension funding, exc compulsory social security
C,J,K	K	CC,JK	18,J,K	66	Activities auxiliary to financial services and insurance activities
I,L	L	IL	I,68	68	Real estate activities
M	MA	M	M	69	Legal and accounting activities
M	MA	M	M	70	Activities of head offices; management consulta activities
M	MA	M	M	71	Architectural and engineering activities; technic testing and analysis
M	MB	M	M	72	Scientific research and development
M	MC	M	M	73	Advertising and market research
M	MC	M	M	74	Other professional, scientific and technical activ
M	MC	M	M	75	Veterinary activities
N	N	N	77,81,82	77	Rental and leasing activities
N	N	N	78	78	Employment activities
N	N	N	79	79	Travel agency, tour operator and other reservatic service and related activities
N	N	N	80	80	Security and investigation activities
N	N	N	77,81,82	81	Services to buildings and landscape activities
N	N	N	77,81,82	82	Office administrative, office support and other business support activities
O	O	O	84	84	Public administration and defence; compulsory social security
P	P	P	85	85	Education

Q	QA	Q	Q		86	Human health activities
Q	QB	Q	Q		87	Residential care activities
Q	QB	Q	Q		88	Social work activities without accommodation
R	R	R	R		90	Creative, arts and entertainment activities
R	R	R	R		91	Libraries, archives, museums and other culture
R	R	R	R		92	Gambling and betting activities
R	R	R	R		93	Sports and recreation activities and amusement
S	S	S	94,96		94	Activities of membership organisations
S	S	S	95		95	Repair of computers and household goods
S	S	S	94,96		96	Other personal service activities
T	T	T	T		97	Activities of households as employers
T	T	T	T		98	Undifferentiated goods-
U	U	U		99	99	Activities of extraterritorial organisations

Appendix B to chapter 3

Figure B1. Model TIMES-CZ schematic structure.



Note: PES – primary energy sources, BC – brown coal, Imp./Exp. – Import/Export, HC – hard coal, PV – photovoltaic, CSP – concentrated solar power, ETS – emission trading system, RES – renewable energy sources, CH2 – compressed hydrogen, LH2 – liquid hydrogen, BM – biomass, ELC – electrical, NPV – net present value, PKM – passenger-kilometre, TKM – ton-kilometre.

Supplementary Materials to chapter 3

Figure S1: Undiscounted annualized costs of the whole energy system (including transport and other sectors) in TEL1 under the BL assumption set (billion €2012)

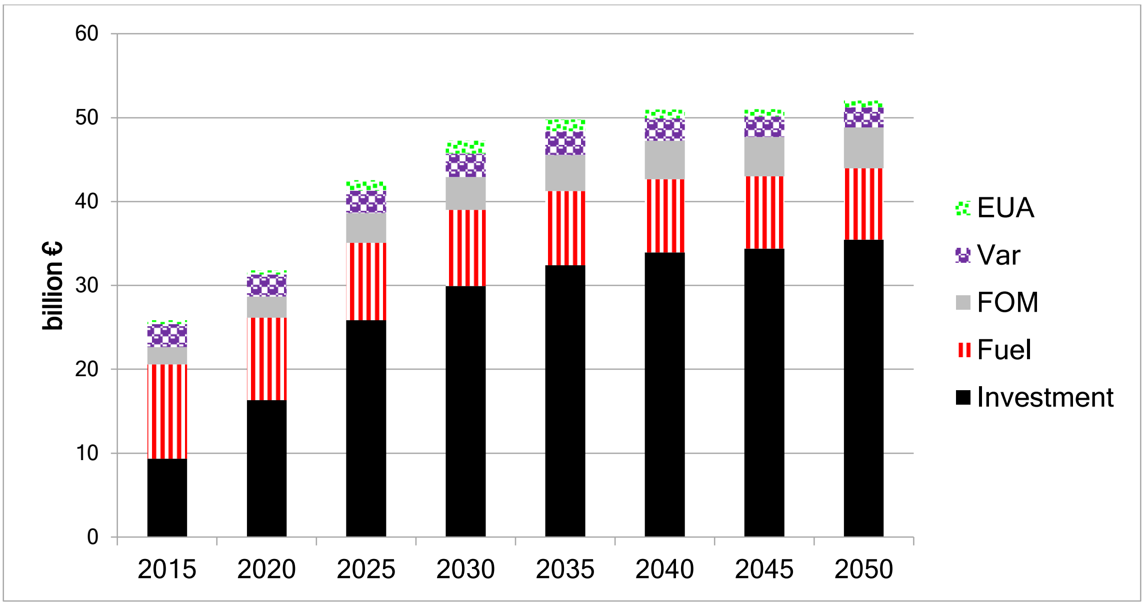
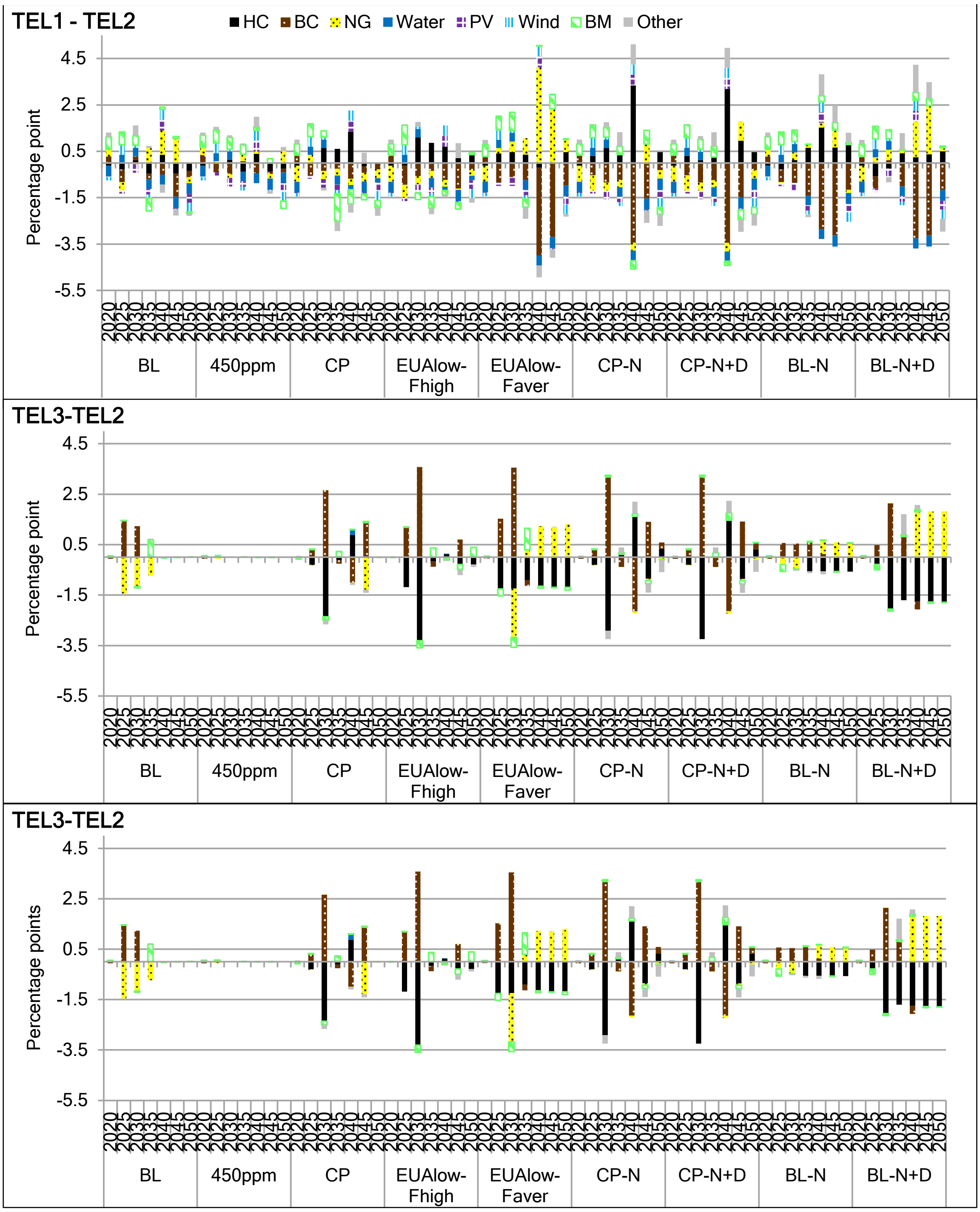


Figure S2: Percentage point difference in the electricity production share between TEL2 other TEL variants in corresponding assumption sets.



Appendix C to chapter 4

Mathematical formulation

The objective function of the model (for more details see Leuthold et al. (2012)) maximizes social welfare

$$\max_{g_{nct}, q_{nt}} \left\{ w = \sum_{n,t} \left(\int_0^{q_{nt}} \pi_{nt}(q_{nt}) q_{nt} - \sum_c g_{nct} M_{nc} \right) \right\}$$

(1)

where π_{nt} is linear inverse demand function with non-negative intercept A_{nt} and negative slope coefficient D_{nt}:

$$\pi_{nt}(q_{nt}) = A_{nt} + D_{nt} q_{nt}$$

(2)

The coefficient M_{nc} is the time-invariant marginal cost of generation for each individual power plant unit *c* at node *n* determined based on the model data. In this paper the ELMOD runs as a cost minimization model as the reference demand values at each node q_{nt} are fixed.

When solving Eq. 1 several energy balance constraints have to be accounted for. The nodal balance constraint (sum of all inflows equals sum of all outflows) has to be true for any node at any point in time:

$$\sum_c g_{nct} + G_{nt}^{wind} + G_{nt}^{solar} + PSP_{nt}^{out} - PSP_{nt}^{in} + \sum_{nn} \theta_{nn,t} B_{n,nn} - q_{nt} = 0 \ \forall n, t$$

(3)

The electricity production from power plant is bounded by the installed capacity of given production unit and cannot exceed this value:

$$g_{nct} \leq G_{ct}^{max}$$

(4)

Electricity flows are modeled by

$$p_{lt} = \sum_n H_{ln} \theta_{nt}$$

(5)

Inequality (6) takes into account the capacity limits of individual transmission lines and restricts the modelled flow to respect these upper and lower bounds respectively.

$$|p_{lt}| \leq \overline{P_l}$$

(6)

The equation (7) sets the voltage angle of an arbitrary node, called slack node, at zero which is important because the uniqueness of the solution of the system is thus guaranteed. Due to the setting of the voltage angle of one variable, all other angle values are relative to this specific one.

$$\theta_{n't} = 0 \ \forall n, t.$$

(7)

$$P_{jk} = B_{jk}\theta_{jk}.$$

(8)

Last steps in obtaining desired result in form of particular line flow incorporate the identification of nodes n,nn and mapping to the lines. For this purpose, Leuthold et al. (2012) uses a special matrix, incidence matrix I_{ln} , which is defined as following:

$$I_{ln} = \begin{cases} 1 & if\ n = j \\ -1 & if\ n = k \\ 0 & else. \end{cases}$$

With the help of series line susceptance B_{ln}, final line power flow (5) can be obtained:

$$H_{ln} = B_{ln} I_{ln}$$

$$p_{lt} = \sum_{n} H_{ln}\theta_{ln}.$$

Referring to the previous text on net input, technical description is added. Net input variable is determined by network susceptance matrix and voltage angles $v_{nt} = \sum_{nn} B_{n,nn}\theta_{n,nn}$. Mathematical derivation of the first parameter, the susceptance matrix $B_{n;nn}$, is based on the above mentioned flow definitions (Leuthold et al. 2012).

Appendix D

Response to Opponents' Reports

I would like to express my gratitude to all opponents for valuable and insightful comments. The opponents' reports helped to improve some parts of the dissertation significantly. Chapter 1 has been extended, Chapter 2 and Chapter 5 have been completed according to recommendations of opponents. The thesis has undergone a careful language editing process and has been completely reformatted.
The response to individual comments is reported below.

Response to Comments from Prof. Ing. Jaroslav Knápek, CSc

Formal point of view: - Numbering the formulas

Response: *Numbering of formulas has been added in Chapter 2.*

Dissertation content:

I recommend somewhat extending the introduction of the work and putting three articles forming the core of the work into the context of the Czech energy development. At the same time, in this context, discuss the importance and benefits of the dissertation author.

Response: *The introduction has been extended and added value of each study is discussed.*

The goal (s) of the dissertation thesis is relatively freely defined / mentioned by one brief paragraph at the end of the introduction of the dissertation. Again, I recommend that the aim of the work be further developed - The work does not have (yet) any formal conclusion. Here, it would be advisable to discuss the results of the work in concert, in conjunction with their topicality, and to discuss further open topics for follow-up research and dissertation work.

Response: *The description of goals of the dissertation has been elaborated more carefully in the introduction. The formal conclusion – Chapter 5 – outlines our further research.*

3. Subsequent comments, remarks and recommendations ad the first solved task: a. The author states that he analyzes the period 1990-2016 in terms of emission trends, however, the images contained in the work show the period 1995-2016 b. How does the author explain the rapid changes in CO emissions between 2001 and 2009? c. In the first decade after 1989, it was possible to use, among other things, the publication published by CENIA Environment in the Czech Republic 1989-2004 (available in the electronic version on the Internet) for discussion of the changes made by the Czech Republic's energy (including the state of the environment including emissions)

Response:

a) *Results in section 2.5 describe the analysis of 1990-2016 period now.*
b) *The largest change in CO emissions between 2007 and 2008 (and in all other emissions) is caused by inconsistency in data, as is discussed in the main text now, and we do not interpret this change in the results. The other fluctuation of CO emissions is caused by low level of CO emission, when change in any big facility can affect the total CO emission from large stationary sources; and parly by lower quality of CO emissions measurement or reporting.*
c) *The suggested publication has been used for description of the first decade after 1989.*

ad. the second task solved a. Tab. 1, p. 36: Specify the price of natural gas (commodity only, final customer price, etc.) b. Pg. 39: The author states that due to the high investment costs and the assumption of absence of RES support, individual limit release scenarios do not lead to different shares of electricity from wind and PV power plants. On the other hand, both types of technology have relatively low investment costs (even with respect to new coal-fired power plants), but the problem is their low utilization of installed power, which then results in higher total cost of electricity c. Pg. 46: I recommend more to explain how to calculate the Annualized cost (including formulas).

Response:

a) *Commodity only price has been specified.*
b) *Thank you for pointing this out. The unclear and misleading formulation has been clarified.*
c) *A footnote with explanation of Annualized cost has been added.*

ad. 3 solved a task (its discussion in General Introduction). The author mentions the absence of further analysis of circular flows in Central Europe. Here you can refer to other sources dealing with this issue or related issues, for example: - Joint study by CEPS, MAVIR, PSE and SEPS on the issue of Unplanned flows in the CEE region. In relation to the common market area Germany - Austria. 2013 - Two Price Zones for the German Electricity Market - Market Implications and Distributional Effects. DIW Berlin German Institute for Economic Research. 2015 - Economic efficiency analysis of introducing smaller bidding zones. Consentec GmbH, 2015. Study for European Energy Exchange AG and EPEX SPOT SE - An Integrated Approach to Model Redispatch and to Assess Potential Benefits of Market Splitting in Germany, EWL Working Paper No. 19/2013 - Loop flows - Final advice. THEMA Report 2013-36 (https://ec.europa.eu/energy/sites/ener/files/documents/201310_loop-flows_study.pdf)

Response: *Relevant literature has been discussed in the Introduction – including all suggested publications. Furthermore, we have noted, the German-Austria bidding zone was splitted on October 1 2018.*

Response to Comments from Prof. Edwin Muchapondwa, Ph.D

Chapter 1

The last paragraph of Chapter 1 treats the suggestions for further research casually. As the thesis rightly indicates that there are several areas requiring further research, they areas should be presented formally in a better detail and as a careful reflection of the incompleteness of the research conducted for the thesis. The only hint currently given is captured in this sentence: "The LMDI decomposition analysis could be accompanied by structural decomposition". How might this new research angle improve on or ameliorate criticisms that could be level towards the current approach.

Response: *The areas requiring further research has been described in Chapter 5.*

Chapter 2

This is a well-executed study but there are bits and pieces which still need to be added towards the end of the chapter. Otherwise the progression of the chapter is on the right path. Additions as specified below are required for the thesis to pass. The use of the "technology" is this statement of page 10 is not very clear: "It suggests firms adjusted their environmental behaviour by improving their environmental technology rather than by changing fuel use or by switching emission intensive fuels by less intensive ones." This should be clarified to be consistent with the general finding that entirely new technologies were not adopted.

Section 2.5 attempts to present results from both the 27 and 35 sector aggregations for the periods 1995 to 2016 and 1990 to 2016. I would suggest keep only one of the analyses in the main text and relegating the other to the appendix. The most important thing is the discussion around the sensitivity of using 27 or 35 sectors across the respective periods.

Section 2.5 should include some discussion of the presented results which will lead to a nice wrap up in section 2.6. These aspects are still missing in the current version.

Response: *The statement of page 10 (now page 17) has been reformulated as follows: "It suggests firms adjusted their environmental behaviour by improving their end-of-pipe technology rather than by switching type fuel or by improving of energy efficiency."*

Section 2.5.1 presents results of analysis of 26 sector aggregation for 1990-2016 period only. Sensitivity of using 18, 26 or 44 sectors across the respective periods is discussed in section 2.5.2. Other results are presented in Appendix A.

Sections 2.5 and 2.6 have been completed.

Chapter 5

This chapter still needs more work. It should ultimately synthesise the issues and findings from the three substantive papers. It needs to bring out the key unified messages from the three papers which were initially written independently of each other.

Response: *Chapter 5 synthesises our findings and outlines areas requiring further research.*

Response to Comments from doc. Silvester van Koten, Ph.D

> As the first article is the least developed article in the dissertation, it might be strategically advisable to make it the last chapter.

Response: *The first article is already finished. We have kept the article on the first place because we believe this article provides a good introduction and context for the following chapters.*

> > "So even though the zone guarantees unrestricted trading and common electricity prices to all participating countries, lack of internal transmission capacity causes significant negative overflows to the transmission systems of neighbouring countries.", p.68/528
>
> It would be good to cite here an earlier paper that brought up these issues already in 2005, namely: Glachant, J. M., & Pignon, V. (2005). Nordic congestion's arrangement as a model for Europe? Physical constraints vs. economic incentives. Utilities policy, 13(2), 153-162.)

Response: *We have discussed the suggested paper in the Introduction on page 7.*

> The clarity of a number of passages in the paper would benefit of more careful proofreading

Response: *The whole thesis has undergone a careful language editing process.*

> "It is very likely that the answer to this question is hidden in the merit order effect. When base-load and cheaply operating nuclear power plants are shut down, electricity supply curve shifts to the left resulting in higher price.",p.73/533

> It would be useful here to present the prices from the simulation that confirm this suggestion. I believe that your model simulates such prices, as it is a fundamental model, right? Or, if not, explain that your model does not create such numbers.

Response: *A footnote with exogenously assumed marginal cost has been added on page 117. The marginal cost are calculated based on exogenously assumed fuel cost, efficiency, corbon content of fuel and price of CO2.*