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THE IMPACT OF VARIABLE RENEWABLE ELECTRICITY ON FULL LOAD HOURS AND EFFICIENCY OF FOSSIL-FIRED POWER PLANTS

MASTER THESIS ENERGY SCIENCE

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Abstract

Variable renewable electricity (VRE) production, consisting of wind power and photovoltaics (PV), has been increasing between 1990-2014 in EU member states. In the latest 10 years, wind power increased more than fivefold from 1.8% in 2004 to 7.9% in 2014 and PV from 0.02% to 2.9%. The share of VRE is not evenly spread over the EU member states. Higher VRE penetration will have a greater effect on a country's power system, as the characteristics of the weather can affect up to 70% of daytime solar capacity due to passing clouds, and 100% of wind capacity on calm days. Currently, renewable electricity variability is generally handled by conventional power plants being cycled to operating at part load level or forced to shut-down. Operating at part load level, or even shutting down completely, leads to a decrease in yearly full load hours of these fossil-fired power plants. Additionally, the conventional power plant base load units are designed to run at constant power to achieve maximum energy efficiency. They tend to have limited operational flexibility and operating at part load levels and increased start-ups of these power plants requires extra fuel consumption, resulting in a lower energy efficiency. In this research, the effect of VRE on the average full load hours and energy efficiency of fossil-fired power plants in the EU from 1990-2014 was determined. EU member states were aggregated into three VRE penetration groups. By aggregating EU member states, the effect of VRE penetration was found by only analysing three groups, instead of 28 individual member countries. Additionally, aggregating the countries increases reliability when comparing the three VRE penetration groups and rules out coincidences in individual countries. With production data from Eurostat and capacity data from the WEPP Database from Platts, the fossil-fired full load hours and energy efficiency for coal and gas-fired power plants were calculated for each year between 1990-2014, for each VRE penetration group. Only within the high and medium VRE penetration group an effect of VRE on fossil full load hours was found. Fossil full load hours were found to decrease by 861 from 3,205 in 2010 to 2,344 in 2014 in VRE-high, while the VRE penetration increased from 17% to 25%, and decreased by 892 from 4,156 in 2010 to 3,264 in 2014 in VRE-medium, while the VRE penetration increased from 5% to 13%. The energy efficiency was found to be very strongly dependent on average year of commission. Only in VRE-high an effect of VRE on energy efficiency was found: the increased VRE penetration from 17% to 25% most likely caused a decrease in coal efficiency from 40% to 38% and a decrease in gas efficiency from 54% to 52% between 2010-2014.

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Abbreviations

ADGT	Aero-derivative gas turbine
CC	Coal combustion
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CHP	Combined heat and power
CO	Carbon monoxide
CO_2	Carbon dioxide
CST	Conventional steam turbine
EU	European Union
FLH	Full load hour
GT	Gas turbine
GHG	Greenhouse gas
H_2	Hydrogen gas
IGCC	Integrated gasification combined cycle
OCGT	Open cycle gas turbine
PCC	Pulverized coal combustion
PV	Photovoltaics
RST	Retrofit steam turbine
SCGT	Simple cycle gas turbine
SPCC	Supercritical pulverized coal combustion
SRMC	Short-run marginal costs
ST	Steam turbine
VRE	Variable renewable electricity

1 Introduction

Climate change is a result of increasing carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions in the earth's atmosphere (Bernstein et al., 2007). In 2013, 32% of the European Union's (EU) GHG emissions was caused by the combustion of fossil fuels in energy industries, highest of all sectors (Eurostat, 2015a). In order to reduce GHG emission from the combustion of fossil fuels in energy industries and therefore the effects of climate change, the EU has set targets for the implementation of renewable energy. In 2050, 80% of the energy supply must be derived from renewable energy sources (European Commission, 2012). This will make a leading contribution to the target of reducing GHG emission by 80-95% in 2050 compared to 1990 levels (European Commission, 2012). Electricity produced from renewable energy sources (i.e. renewable electricity) has increased over the last 10 years from 14.4% in 2004 to 27.5% in 2014, and the target for 2020 is 35% (Eurostat, 2015b). The current share of renewable electricity is not evenly spread over the EU member states. According to data from Eurostat (2016), in 2014 the share of renewable electricity was highest in Austria (70.0%), Sweden (63.3%) and Portugal (52.1%) and the share was lowest in Malta (3.3%), Luxembourg (5.9%) and Hungary (7.3%). The high shares of renewable electricity consist predominantly of hydropower and biomass. However, the growth of electricity generated from renewable energy sources in the past ten years largely reflects an expansion of wind power and photovoltaics (PV). Wind power increased more than fivefold between 2004 and 2014 from 1.8% to 7.9% share of total gross electricity generation. The relative growth of PV was even greater, increasing from 0.02% to 2.9% share of total gross electricity generation within the same timeframe. Similar to the overall percentage of renewable electricity, the share of wind and PV is not evenly spread over the EU member states. The highest shares of wind in 2014 are found in Denmark (40.6%), Portugal (22.9%) and Ireland (19.5%), while the highest shares of PV are found in Italy (8.0%), Greece (7.5%) and Germany (5.7%).

The variability in energy sources wind and solar, caused by the characteristics of the weather, has implications for transmission and distribution systems (Georgilakis, 2008). The characteristics of the weather can affect up to 70% of daytime solar capacity due to passing clouds, and 100% of wind capacity on calm days (APS, 2011). These uncertainties are much greater than the traditional uncertainties of a few percent in demand forecasting. Intermittency of variable renewable electricity (VRE) sources wind and solar becomes increasingly difficult to manage as their penetration levels increase (Charles River Associates, 2010). Typically, wind and PV shares up to 30% are considered feasible to be integrated in the grid, whereas higher shares will require new approaches for grid management (APS, 2011).

This variability can be accommodated when renewable energy resources are expecting to decrease by using fast-acting conventional reserves, demand-side management, installing large scale energy storage on the grid, or by upgrading the capacity of long distance transmission lines which enables access to larger pools of resources to balance regional and local excesses or deficits (IEA, 2008; Van Hulle & Gardner, 2008). Due to the (yet) undeveloped status of demand-side management and high costs of the latter two options, currently renewable energy variability is generally handled by conventional power plants being started-up and-shut down, ramped up and down, and operated at part load levels more frequently (Braun, 2014; Göransson & Johnsson, 2009; Holttinen & Pedersen, 2003; Tuohy et. al, 2009). Ramping down to operating at part load level, or even shutting down completely, leads to a decrease in yearly full load hours of these fossil-fired power plants. The conventional power plant base load units are designed to run at constant power to achieve maximum energy efficiency. They tend to have limited operational flexibility and cycling to operating at part load levels and increased start-ups of these power plants results, besides serious degradation of plant equipment through mechanisms such as thermal fatigue, erosion, corrosion etc. leading to increased operation and maintenance costs and eventually a reduced plant lifetime, in a lower energy efficiency due to the increased fuel consumption (Troy, 2011).

By taking into account all of the abovementioned aspects, the following main research question and sub-questions are formulated:

What has been the effect of variable renewable electricity implementation in the European Union from 1990-2014 on the full load hours and energy efficiency of fossil-fired power plants?

- *What are the expected impacts of variable renewable electricity on full load hours and energy efficiency of fossil-fired power plants based on literature?*
- *How has the variable renewable electricity penetration developed in the EU member states?*
- *How have the full load hours of fossil-fired power plants developed in EU member states?*
- *How has the energy efficiency of fossil-fired power plants developed in EU member states?*
- *Is the development of full load hours and energy efficiency in EU member states affected by factors other than variable renewable electricity penetration?*

In chapter 2, the theoretical framework of this research is provided. Chapter 3 discusses the methodology which was used to obtain the results presented in chapter 4. After detailed elaboration of the results the discussion and conclusion are presented in chapter 5 and 6, respectively. Finally, chapter 7 contains the list of literature used in this research and chapter 8 the appendices.

2 Theory

Electricity generation is the process of generating electric energy from primary energy sources. Electricity is generated at a power plant by electromechanical generators often driven by turbines fuelled by heat or steam produced by the combustion of a type of coal, gas or oil, or driven by heat from nuclear fission. In 2014, 72.5% of total electricity consumed in the EU was generated from thermal energy sources. The remaining 27.5% was generated through renewable energy sources consisting of hydropower, wind, PV and combustion of biomass (Eurostat, 2016).

Every country has its own electricity mix, i.e. different capacities installed of the various types of renewable and non-renewable electricity generation. A country's total generation capacity is normally at least equal to its peak demand, in order to maintain security of supply (Joskow, 2006). Peak demand only occurs a fraction of the day so most frequently the electricity demand is well below the total available generation capacity. To determine which electrical generators should be operating in those cases, the merit order ranks the available sources of electrical generation based on their short-run marginal costs (SRMC). SRMC describe the costs of producing a small amount of additional electrical energy (El-Keib & Ma, 1997). In centralized energy management of EU member states, ranking is so that electricity generators with the lowest SRMC are the first to start producing electricity to meet demand, and electricity generators with the highest SRMC last (Joskow & Kahn, 2001). Dispatching based on this method ensures the costs of producing electricity are minimized. The SRMC of renewable electricity produced from hydropower, wind and PV are close to zero due to the lacking of fuel costs. The marginal costs of renewables consists only of operating costs (Timmons et al., 2014). Therefore, if for example wind speeds suddenly pick up, the generated electricity is in principle always consumed. Other non-renewable electricity generators need to compensate in this case, generally based on the SRMC, by cycling down to operating at part load levels or shutting down completely (Holttinen, 2005). However, sometimes electricity generators are dispatched out of the merit order due to limited operational flexibility properties. The (fuel) type, size and age of the electricity generator determine the start-up time, minimum up-time, minimum down-time, minimum running capacity and the maximum cycling speed. These restricting factors can cause an out of merit order dispatch (Dijkema et al., 2009).

2.1 Types of power plants and their flexibility

Compensation by fossil-fired power plants for the intermittency of VRE generation is required on long- and short-term (i.e. from days to minutes) (Ummels et. al, 2007). In general, the order of suitableness in modern power plants for cycling up and down within a short time frame is pumped storage, hydropower plant, simple cycle gas turbine (SCGT) plant, combined cycle gas turbine (CCGT) plant, coal-fired power plant and lastly nuclear power plant (IEA, 2011). However, the age of a power plants has a high influence on this order of flexibility. For example, a modern coal-fired power plant is most likely more flexible than most of the 20-year old SCGT plants.

The abovementioned power plants can be categorized in three groups: base load units, mid-merit units and peaking units (Troy, 2011). Base load units operate at constant, full power throughout the whole day to achieve maximum fuel efficiency. Hydropower, biomass, nuclear, geothermal, coal and CCGT plants belong to this category. Base load units (except for hydropower) tend to have limited operational flexibility. Mid-merit units, or load following power plants, follow the daily demand profile, producing most of their electricity during the day and cycling or shutting-down during the night. Depending on their individual flexibility, coal-fired and CCGT plants can also belong in this category, next to the SCGT plants. The fastest reacting category are the peak units. These generators only operate at peaks and can generally respond very quickly to, for example to sudden changes in VRE output. Peak units consist mostly of small SCGTs and pumped storage. (Troy, 2011)

The cycling down to operating at part load level, or shutting down completely, affects the total yearly electricity output of all categories of generators, which is expressed as a capacity factor or as full load hours (Blanco, 2009). A capacity factor of 100% equals 8760 full load hours. The operating at part load levels and start-ups after forced shut-downs of these electricity generators requires increased fuel consumption compared to operating at constant full load, for which base load units are designed (Troy, 2011). This increased fuel consumption leads to a decrease in the plant's energy efficiency (le Pair et al., 2012). So compensation by fossil-fired power plants for the intermittency of VRE generation affects their yearly full load hours and energy efficiency.

Example Germany

In Figure 1, the German electricity mix of a typical week is presented (week 11, 2016). This figure illustrates how fossil-fired power plants react to VRE production in Germany. At the bottom of the figure, base load power consisting of hydro, biomass and nuclear are presented. Hydropower and biomass are renewable energy sources utilized as base load power. Nuclear power is due to its economic and operational properties (i.e. inflexibility) utilized as base load power. These base load power generators are not affected by either night/day demand fluctuations or VRE production. Above nuclear, the production of the coal-fired power plants are presented. Even though coal-fired power plants are originally designed for base load power production, in Germany coal-fired power plants have been modified to improve flexibility. Coal-fired power plants fuelled by brown coal are base load units but a share of the plants fuelled by hard coal are considered mid-merit power generators. These generators adjust to the night/day fluctuating demand but also to the intermittent production of wind and PV. Electricity production from gas-fired power plants remains fairly constant over the 7-day period, however some increases are visible during electricity demand peaks. The CCGTs will most likely be used for base load power while the smaller installed capacity of SCGTs are used as peaking units. The final non-VRE power generator is pumped storage, which is due to its high flexibility only used as peaking unit.

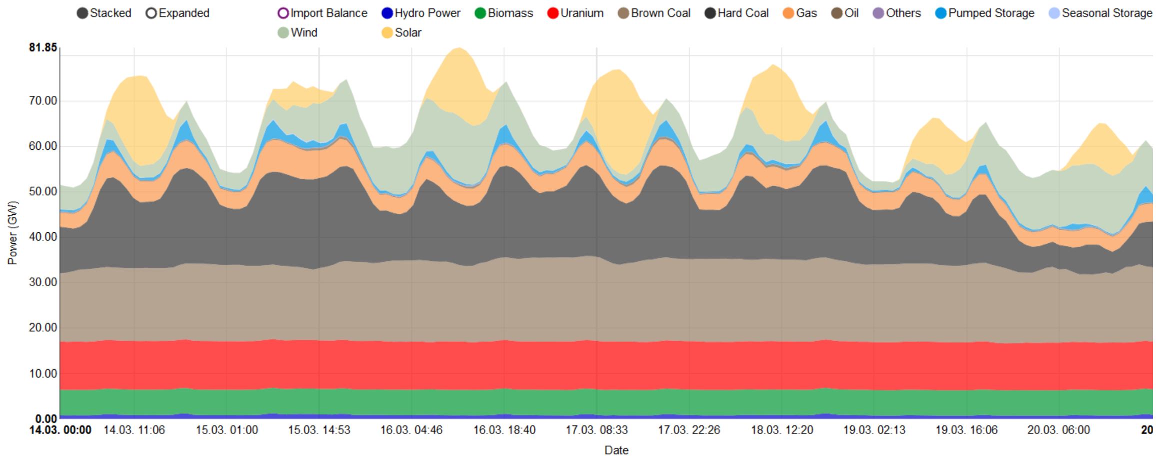

Figure 1: Electricity production mix in Germany, week 11 2016 (Fraunhofer ISE, 2016a).

2.2 Causal diagram

As discussed, the average fossil-fired full load hours and average fossil-fired energy efficiency of power plants in a country are affected by VRE penetration within that country. In Figure 2 below, the causal diagram is presented between VRE penetration, average full load hours of fossil-fired power plants, average energy efficiency of fossil-fired power plants, and other relevant factors which are related to these indicators. For each relationship, it is indicated whether the relationship is positive or negative. A distinction is made between factors on country level and plant level, so for example the total volume of electricity generation regards the electricity generation for the whole country, and the SRMC regards the cost of a single power plants (e.g. coal-fired, gas-fired, nuclear etc.).

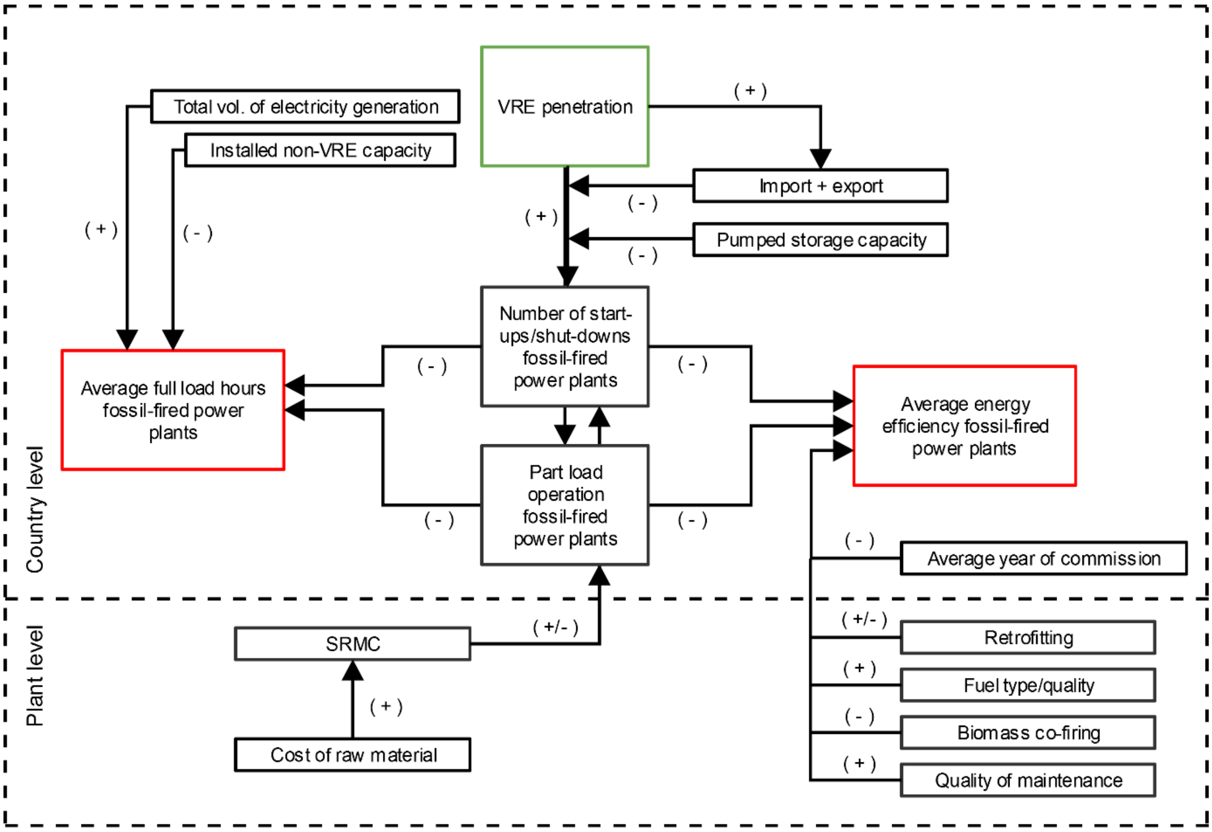

Figure 2: Causal diagram between VRE and full load hours and energy efficiency.

2.2.1 Plant level

SRMC and cost of raw material

Power plants are classified in the merit order based on their short-run marginal costs. Part of the SRMC is determined by the cost of raw material. A higher cost of for example natural gas will cause the SRMC of natural gas-fired power plants to increase. However, every power plant, regardless of whether it operates on the same primary fuel, has its individual SRMC due to power plant performance characteristics (El-Keib & Ma, 1997). The SRMC of individual power plants affect the number of start-ups/shut-downs and part load operation of fossil-fired power plants positively or negatively, as for example a gas-fired power plant being replaced by a coal-fired power plant have the opposite effect on the total number of start-ups/shut-downs and average part load operation of fossil-fired power plants (Appunn, 2015).

Retrofitting, fuel type/quality, biomass co-firing and quality of maintenance

Retrofitting of power plants describes the addition of new/upgraded technology or replacement of old technology in existing power plants. Even though new technology may be added to a power plant, or old technology may be replaced, the energy efficiency is not by definition increased with retrofitting. Besides cases where the energy efficiency does increase through for example the addition of energy saving technology or implementation of state of the art technology with an inherent higher efficiency (e.g. Bronicki & Fisher, 2004), cases exist where the energy efficiency decreases through retrofitting (e.g. Goto et al., 2013), mainly when retrofitting is aimed at reducing the plant's CO_2 emissions by carbon capture and storage (CCS). Besides the possible energy efficiency effects caused by retrofitting, energy efficiency decreases with the co-firing of biomass (Tillman, 2000). The fuel quality affects the energy efficiency positively, as higher quality fuel types (e.g. bituminous coal vs. lignite) have increased energetic content and cleanness (Opara et al., 2012). Lastly, the quality and type of maintenance applied to the power plant influences the energy efficiency positively: higher quality of maintenance results in a higher efficiency while low quality of maintenance results in a lower energy efficiency (Srikrishna et al., 1996; Szwedo, 2012).

2.2.2 Country level

Average year of commission

The average year of commission of fossil-fired power plants in a country affects the average energy efficiency of the power plants (Campbell, 2013). Technology developments cause the efficiency of newly constructed fossil-fired power plants to increase over time (Graus et al., 2007). For example, the average efficiency of gas-fired power plants in a country will increase if an old SCGT is retired and replaced by a modern CCGT (i.e. an increase in average year of commission of gas-fired capacity).

Total volume of electricity generation, non-VRE capacity and VRE penetration

Total volume of electricity generation (referred to as total electricity generation from this point onwards), installed non-VRE capacity and VRE penetration directly affect the average full load hours of fossil-fired power plants in a country. A decrease in the total electricity generation will decrease the full load hours of fossil-fired power plants, assuming the non-VRE capacity and VRE penetration remain constant. Oppositely, the fossil full load hours increase if power plants are decommissioned, leading to a decrease in non-VRE capacity, assuming the total electricity generation and VRE penetration remain constant. However, power plants can only be decommissioned if the remaining non-VRE capacity can maintain security of supply (in combination with import capacities), by being able to meet the peak demand when there is no wind and sun. Similarly to non-VRE capacity, an increase in VRE penetration will cause a decrease in fossil-fired full load hours, assuming the total electricity generation and non-VRE capacity remain constant, as the extra output of VRE replaces part of the fossil-fired electricity generation (Troy, 2011).

Import + export and pumped storage

The power systems of, for example, the Nordic countries (Sweden, Denmark, Finland, Iceland and Norway) are strongly interlinked by cross border transmission lines, allowing importing and exporting of electricity between these countries. These connections strengthen the security of supply and ensure cost-efficient production (Swedish Energy Markets Inspectorate, 2015). More importantly for this research, the aggregated power market enables the integration of high shares of VRE. Overproduction of VRE in one country can be exported to neighbouring countries instead of ramping-down or even shutting down fossil-fired power plants (Troy, 2011). Oppositely, a sudden decrease in VRE output in a country can be compensated by overcapacity from interlinked countries. Additionally, pumped hydropower storage, widely available in Norway where the total storage capacity is equal to 70% of the annual electricity generation (Killingtveit, 2012), is used for reacting to sudden changes in VRE output within the region (Eurelectric, 2015). The cross border transmission lines enable a major part of the overproduction of VRE to be stored in water reservoirs in Norway, after which the stored energy can be released again during periods of low VRE output. The higher the pumped storage and import/export capacity in a country or region, the higher VRE penetration can be implemented without affecting the performance of fossil-fired power plants (Brown et al., 2007). Therefore, the full load hours and energy efficiency of fossil-fired power plants in countries with high import + export and/or pumped storage capacity will be affected less by VRE penetration (Troy, 2011).

The research aim is to compare the performance of fossil-fired power plants in the EU. In order to maintain a realistic scope for this research, only the factors on country level will be taken into account, as data on plant level is not made (easily) accessible due to competition advantages. Only pumped storage is excluded from the factors on country level, as the average share is minimal in EU countries: 0.99% in 2014. Even though Nordic countries may benefit from the large pumped storage capacity in non-EU country Norway, this effect is taken into account by including import + export.

3 Methodology

The methodology of this research consists of five steps. First, VRE effects on full load hours and energy efficiency of fossil-fired power plants were analysed in literature. Second, the VRE penetration was calculated for the EU member countries. Third and fourth, the trends in full load hours and energy efficiency were calculated. Fifth and last, the results found in literature were compared with the findings of this research.

3.1 Variable renewable electricity effects according to literature

In the first step, the effects of VRE on full load hours and energy efficiency of fossil-fired power plants were analysed in literature. As discussed in the Introduction and Theory chapters, and widely found in literature, an increased share of VRE will affect the full load hours of fossil-fired power plants (e.g. GE Energy, 2010; Moreno & Martínez-Val, 2011; Sensfuß et al. 2008). Due to the increased public awareness for CO_2 emissions, considerable literature is available which models and quantifies the effect of increasing VRE penetration in a country or area expressed as CO_2 emission reduction, caused by decreased full load hours of the fossil-fired power plants (e.g. Holttinen & Tuhkanen, 2004; Kaffine et al., 2012). However, CO_2 emissions cannot be accurately calculated back to reduction in full load hours. Therefore, the decision was made to focus on studies which model the effect of increased VRE in the future, to determine the effect on full load hours. The energy efficiency of fossil-fired power plants is affected through increased start-ups and part load operation, as discussed in the Introduction and Theory chapters. Therefore, for energy efficiency effects of VRE, literature was used in which the effect of increased start-ups and part load operation on energy efficiency was quantified.

3.2 Shares of variable renewable electricity in EU member states

In the second step, the VRE penetration in EU member states was calculated for each year between 1990-2014 with the following equation:

$$VRE = \frac{E_{Wind,main} + E_{Wind,auto} + E_{PV,main} + E_{PV,auto} + E_{ST,main} + E_{ST,main}}{E_{tot}}$$

Where:

VRE = VRE penetration (%)
$E_{Wind,main}$ = Gross electricity generation Main activity electricity only – Wind (TWh/year)
$E_{Wind,auto}$ = Gross electricity generation Autoproducer electricity only – Wind (TWh/year)
$E_{PV,main}$ = Gross electricity generation Main activity electricity only – PV (TWh/year)
$E_{PV,auto}$ = Gross electricity generation Autoproducer electricity only – PV (TWh/year)
$E_{ST,main}$ = Gross electricity generation Main activity electricity only – Solar thermal (TWh/year)
$E_{ST,main}$ = Gross electricity generation Autoproducer electricity only –Solar thermal (TWh/year)
E_{tot} = Total gross electricity generation Main activity + Autoproducer (TWh/year)

All data was obtained from Eurostat (2016). A power plant classified as *Main activity electricity only* are privately or publicly owned installations which generate electricity to sell to third parties as their principal activity. *Autoproducers* generate electricity partly or wholly for their own consumption. A decision was made to include both in calculating VRE penetrations. During sunny periods and/or high winds, autoproducers may generate more electricity than they can consume, resulting in back feeding of excess electricity into the grid, for which fossil-fired power plants may need to compensate.

Based on the VRE penetration in 2014, three groups were made in which countries were aggregated to form a group with high, medium and low penetration VRE. This way, the effect of VRE penetration on fossil full load hours and energy efficiency was identified by only comparing three (aggregated country) groups, instead of 28 individual EU member states. The additional benefit of aggregating countries is that coincidences are ruled out when comparing the three VRE penetration groups and conclusions are more reliable. The disadvantage of aggregating countries is that a large country within a group can be dominant for the group's results. Because of this, individual country results were presented in cases where single country dominancy was found.

3.3 Full load hours

As discussed in the Theory, full load hours of fossil-fired power plants are mainly influenced by three factors: total electricity generation, non-VRE capacity and VRE penetration. First, for each VRE penetration group, data on (gross) electricity generation was collected from European Commission (2016). The total electricity generation was divided into fuel types coal, gas, oil, nuclear, VRE and other renewables (hydropower, biomass, geothermal, tide, wave and ocean). The non-VRE capacity was obtained from European Commission (2016) as well. The non-VRE capacity was obtained by adding the installed capacity of combustible fuels, nuclear, hydro and other sources. The third factor, VRE penetration, was calculated in the same manner as described in the previous paragraph, but aggregated for the countries within the VRE penetration group.

Next, the full load hours per fossil fuel for the VRE penetration groups were calculated in each year between 1990-2014 with the following formula:

$$FLHs_f = \frac{E_f}{Cap_f * 365d * 24h} * 8760h$$

Where:

$FLHs_f$ = Full load hours, fuel f
E_f = Gross electricity generation, fuel f
Cap_f = Installed capacity, fuel f

The electricity generation data was obtained from the European Commission (2016). The installed capacity data from European Commission (2016) does not make a distinction between installed capacity of combustible fuels. Therefore capacity data from the UDI World Electric Power Plants (WEPP) Database was used (Platts, 2011). This database contains all power plants in the EU, including both *main activity electricity only* producers as *autoproducers*. No distinction between the two types is made within the WEPP Database, so therefore the calculated full load hours represent both of these types of producers. The individual power plants were divided into the three fuel groups based on their listed primary fuel in the WEPP Database. The power plants categorized into coal consisted of plants with primary fuel of either coal hard, -soft, -generic, -gas, -waste or -peat. For natural gas, the plants had either natural gas or process gas listed as primary fuel. Finally, for oil, the plants had either heavy or light oil listed as primary fuel. In the WEPP Database, for each power plant was specified on which date the plants were commissioned and, if applicable, decommissioned. The listed dates were rounded off to the nearest year, meaning a power plant decommissioned on June 30, 2010 was considered to be offline for the whole year 2010, while a power plants decommissioned on July 1, 2010 was considered to be online for the whole year 2010. For each power plant, the maximum nameplate capacity was used. The WEPP Database provided for this research was updated until 2011. For the smaller countries (Austria, Belgium, Bulgaria, Cyprus, Denmark, Estonia, Finland, Greece, Hungary, Ireland, Malta, Poland, Portugal, Romania, Slovakia, Slovenia and Sweden) the decommissioned and newly construction power plants were manually edited and added to the database based on press statements and news articles. However, for the larger countries (France, Germany, Italy, The Netherlands, Spain and the United Kingdom), the list of power plants was considered too extensive, making the process too time consuming to correctly, manually determine the capacities between 2012-2014. Therefore, national statistics were consulted to determine the capacities in the most recent three years. Since national statistics of the overlapping year 2011 were found to be deviating from the value obtained from Platts (2011), the yearly percentages increase/decrease from national statistics until 2014 were applied to the latest value obtained from Platts (2011) in 2011. The percentage from which national statistics differed from the total fossil-fired capacity in 2011 from Platts (2011), together with the source where the national statistics were obtained, are listed in Table 1 below.

Table 1: National statistics sources used for determining installed capacity between 2012-2014.

Country	Source	Difference national statistics (2011) vs. Platts (2011)
France	RTE (2016)	+30.6%
Germany	Fraunhofer ISE (2016)	-2.1%
Italy	Terna (2016)	+11.2%
The Netherlands	TenneT (2016)	-1.3%
Spain	REE (2015)	-8.3%
United Kingdom	Carbon Brief (2015)	-8.5%

The largest differences were found in France and Italy, where the installed fossil-fired capacity from national statistics in 2011 were found to be 30.6% and 11.2% higher than the values found in Platts (2011). The national statistics do not specify data of individual power plants, so a thorough analysis of which source is incorrect could not be completed. However, full load hours of gas-fired power plants were found to be unrealistically high for some periods within the two countries, taken into account that the availability of gas-fired power plants is around 7,446 (Tidball et al., 2010), for example in 2000 in France: 8,059 and in 1990 in Italy: 8,760. These unrealistically high values indicate that the data from Platts (2011) may be incomplete for these countries. In Spain and United Kingdom the national statistics for installed fossil-fired capacity were found to be lower by 8.3% and 8.5%, respectively, compared to the data found in Platts (2011). This difference may possibly be caused by the excluding of autoproducer power plants in national statistics. However, this could not be proven as this was found to be unspecified in the national statistics data. Finally, the smallest difference were found in Germany and The Netherlands, which were found to be deviating by only 2.1% and 1.3%, respectively.

After full load hours for the individual fossil fuels were calculated, the weighted average full load hours for the fossil-fired power plants were calculated with the following formula:

$$FLH_{fossil} = \frac{FLH_{coal} * Cap_{coal} + FLH_{gas} * Cap_{gas} + FLH_{oil} * Cap_{oil}}{(Cap_{coal} + Cap_{gas} + Cap_{oil}) * 365d/y * 24h/d} * 8760h$$

Where:

FLH_{fossil} = Average full load hours fossil-fired power plant
FLH_{coal} = Average full load hours coal-fired power plant
Cap_{coal} = Installed coal capacity (MW)
FLH_{gas} = Average full load hours gas-fired power plant
Cap_{gas} = Installed gas capacity (MW)
FLH_{oil} = Average full load hours oil-fired power plant
Cap_{oil} = Installed oil capacity (MW)

After calculating the full load hours, the import + export for the VRE penetration groups, expressed as share of total electricity generation, was calculated from European Commission (2016) and plotted against the earlier calculated VRE penetration trend. The correlation was then calculated between VRE generation and import + export in all three VRE penetration groups to determine if import + export was found to be dependent on VRE output. The classification of correlations used in this research were: 0-0.19 very weak, 0.2-0.39 weak, 0.40-0.59 moderate, 0.6-0.79 strong and 0.8-1 very strong.

3.4 Energy efficiency

The methodology used for calculating the efficiency is based on the "Handbook of International Comparisons of Energy Efficiency in the Manufacturing Industry" by Phylipsen et al. (1998) which is used in, among others, the report by leading energy consultancy Ecofys on comparing international energy efficiencies (Hussy et al., 2014):

$$E = \frac{P + H * s}{I}$$

Where:

E	= Energy efficiency (%)
P	= Power generation from public power plants and public CHP plants (TWh)
H	= Heat output from public CHP plants (TWh)
s	= Correction factor between heat and electricity
I	= Primary energy input for public power plants and public CHP plants (TWh)

All data was obtained from Eurostat (2016). S is the correction factor between heat and electricity, which is defined as the reduction in electricity generation per unit of heat extracted. The correction factor s reflects the amount of electricity generation lost per unit of heat extracted from the electricity generator. According to Graus & Worrell (2009), for district heating systems this value is between 0.15 and 0.2 and therefore a value of 0.175 was used.

In contrast to the full load hour calculations, where autoproducers were included as the WEPP Database did not make a distinction between main activity electricity only and autoproducer plants, in energy efficiency calculations autoproducers were excluded. This decision was made due to autoproducer CHP plants. The fuel input of these plants consists only of the part that is sold, not the part which is consumed within the autoproducer's establishment (InterEnerStat, 2016). Therefore, the efficiencies of autoproducer CHP plants would turn out higher than realistic. This has an unwanted influence on the efficiency trends in the VRE penetration groups, which is why the decision was made to exclude autoproducers from the energy efficiency calculations. In Figure 42 in Appendix A, the gas efficiencies for EU member states including both main activity as autoproducer plants are presented to indicate what the effect would be of including autoproducers in efficiency calculations.

The power (P) and heat (H) generation data used for these calculations are measured as gross electricity and heat generation. The difference between gross and net is the subtraction of the auxiliary electricity consumption and losses occurring in transformers at the power station. The efficiency losses due to auxiliary equipment is typically 1.5-3 percent points for coal-fired power plants and 1-2 percent points for natural-gas fired power plants (FirstEnergy Corp, 1999). The calculated efficiencies therefore do not reflect the net electrical output.

Another note should be made that the energy inputs (I) from Eurostat (2016) are based on lower heating value (LHV). This causes the calculated efficiencies to be higher than when calculated with higher heating value (HHV). The efficiencies are dependent on fuel characteristics but are generally considered to be around 3% higher for coal, 10% higher for gas and 7% higher for oil, when using data based on LHV compared to HHV (Graus & Worrell, 2009).

The efficiencies were only calculated for coal- and gas-fired capacity, as the input data for oil, consisting of crude oil, naphtha, kerosene type jet fuel, other kerosene, gas/diesel oil, fuel oil, petroleum coke, other oil products, bitumen, LPG and refinery gas, was found to be incorrect for several countries in the VRE penetration groups, leading to incorrect and unrealistically high efficiency values. Taken into account that oil-fired power plants are outdated and phased out gradually within the EU member states, no efforts were made to find correct data as it was considered to be the least relevant fuel group for the research. In Figure 43 in Appendix B, the calculated oil efficiencies are presented. Coal consisted of anthracite, coking coal, other bituminous coal, sub-bituminous coal, lignite/brown coal, peat, coke oven coal, coal tar, BKB, peat products, coke over gas, blast furnace gas and other recovered gasses. For gas only natural gas was taken.

The trends in energy efficiency for coal- and gas-fired power plants of the VRE penetration groups were then plotted with the trend in average year of commission. The average year of commission for coal and gas were calculated from data from Platts (2011), with the following formula:

$$YoC = \frac{\sum_{i=x}^{n} Cap_x * Y_x}{\sum_{i=x}^{n} Cap_x}$$

Where:

YoC = Average year of commission
Cap_x = Capacity, power plant x (MW)
Y_x = Year of commission, power plant x

The WEPP Database was updated until 2011. However, planned or expected decommissioning and construction of power plants after 2011 were included in the database. These planned or expected modifications to the database are highly uncertain, as most of the planned and expected modifications were found to be delayed or cancelled. This caused inaccurate values of average year of commission to be obtained between 2012-2014. Therefore, these years were not included in the average year of commission trends. The 21 data point from 1990-2011 were considered to still be more than sufficient to identify a trend. The trends in average year of commission and energy efficiency of coal and gas were then plotted to calculate the correlation in all three VRE penetration groups, to determine if the energy efficiency was dependent on the average year of commission.

3.5 Comparing results with literature

In the final step, the results found in literature were compared with the results of this research, obtained by the steps discussed in paragraph 3.2-3.4, to determine whether the effects of VRE on the full load hours and energy efficiency of fossil-fired power plants complied.

4 Results

In this chapter, first the results of the literature study are presented. Then, the development of VRE penetration in EU member states is presented. Based on these VRE penetrations, three VRE penetration groups are determined. For each VRE penetration group the trends in full load hours and energy efficiencies are presented. After elaborating the trends within these three VRE penetration groups, the trends are compared to each other. Finally, the results from literature are compared to the results of this research.

4.1 Variable renewable electricity effects according to literature

The results of the literature study are split up into effects on full load hours and effects of energy efficiency. Energy efficiency effects are split up further into effects caused by increased start-ups and effects caused by part load operation.

4.1.1 Full load hours

In the following section, results of previous studies are discussed, consisting of renewable integration studies of grid operators and consultancies, and published articles by leading authors. In Table 2, a summary is provided of the literature studies regarding full load hours. In the table, the capacity factors of the individual studies have been recalculated to full load hours, the capacity indicator used in this research.

Table 2: Summary of full load hour studies.

Study	Scenario	VRE%	Coal	CCGT	SCGT	SCGT peak	Oil
Southwest Power Pool	Base case	4%	7,183	5,606	n/a	2,278	n/a
Wind Integration Study	Scenario 1	10%	7,008	4,818	n/a	2,278	n/a
(Charles River Associates, 2010)	Scenario 2	20%	6,658	4,117	n/a	2,278	n/a
New York ISO Wind	Base case	4%	7,350	5,519	2,374	710	858
Integration Study	Scenario 1	13%	7,271	5,046	2,059	622	788
(NYISO, 2010)	Scenario 2	19%	7,174	5,046	1,927	587	771
	Scenario 3	25%	7,174	4,809	1,971	701	823
7.55 GW Study	Base case	15%	6,570	6,920	n/a	n/a	n/a
(Troy, 2011)	Scenario 1	29%	6,044	6,395	n/a	n/a	n/a
	Scenario 2	43%	5,782	5,256	n/a	n/a	n/a
9.6 GW Study	Base case	11%	7,008	7,621	n/a	n/a	n/a
(Troy, 2011)	Scenario 1	23%	6,658	7,183	n/a	n/a	n/a
	Scenario 2	34%	6,482	6,482	n/a	n/a	n/a

In the Southwest Power Pool (SPP) wind integration study by Charles River Associates (2010), the operational and reliability impacts of integrating wind power into the SPP were investigated. The SPP region consists of 11 regional utility companies located in among others Texas, Arkansas, Louisiana and Mississippi. Within this region, the starting situation (i.e. base case) consists of 4% VRE penetration, consisting only of wind power. The remaining electricity was generated primarily by coal (76%), followed by natural gas (14%), nuclear (9%) and hydro (1%). Two scenarios were simulated: 10% Case and 20% Case, in which the wind penetration was increased from 4% to 10% and 20%, respectively. In Table 3, the results of this study are presented. In the 10% Case, results showed that the capacity factors of the base load units and mid-merit units (coal fired-power plants and CCGT plants) generated less, as this generation was displaced by wind generation. The capacity factors decreased from 64% to 55% for CCGT plants and 82% to 80% for coal-fired power plants. The capacity factor of the natural gas-fired peaking units remained unchanged (26%). However, if looking at the individual capacity factors of the peaking units, the capacity factor increased in areas where wind power was implemented (from 17.8% to 22.5%), but decreased in other areas, resulting in the overall capacity factor remaining unchanged. In the 20% Case, the capacity factors of CCGT plants and coal-fired power plants decreased even further to 47% and 76%, respectively. The increased wind penetration displaced even more base load and mid-merit generation in this scenario. The overall capacity factor of the natural gas-fired peaking units remained similarly to the 10% Case scenario unchanged. The individual capacity factors however did experience increased fluctuations, again dependent on location.

Table 3: Southwest Power Pool study results on capacity (Charles River Associates, 2010).

Plant	Base case (4% VRE)	10% VRE	20% VRE
CCGT	64%	55%	47%
SCGT (peaking units)	26%	26%	26%
Coal	82%	80%	76%

In the wind integration study of the New York Independent System Operator (NYISO, 2010), three scenarios were investigated in which wind penetration was increased. In the base case scenario in 2013, the wind penetration was 4%. Besides wind power the energy landscape was dominantly natural gas-fired (52%), followed by nuclear (15%), hydropower and pumped storage (15%), oil (9%) and coal (6%). The scenarios simulated were increasing wind penetration to 13.3%, 18.8% and 25.0%. The results are presented in Table 4 below. The natural gas-fired power plants were split up into small SCGT peaking units (SCGT-Peak) and base load/mid-merit units consisting of large capacity SCGT and CCGT plants.

Table 4: Capacity factors NYISO scenarios (NYISO, 2010).

Plant	Base case (4% VRE)	13.3% VRE	18.8% VRE	25.0% VRE
SCGT-Peak	8.1%	7.1%	6.7%	8.0%
SCGT	27.1%	23.5%	22.0%	22.5%
CCGT	63.0%	57.6%	57.6%	54.9%
Oil	9.8%	9.0%	8.8%	9.4%
Coal	83.9%	83.0%	81.9%	81.9%

As shown in the table above, the capacity factors of the SCGT and CCGT plants generally decreased as the wind penetration increased. Wind power displaced the base load power from natural gas in this case. However, the SCGT plants experienced a small increase in capacity factor between the 18.88% and 25.0% VRE scenario. This was caused by the increased need for flexible power generation due to the intermittency of VRE. As SCGT plants are more flexible than CCGT plants, the SCGTs were pushed into mid-merit position and used to compensate variations in VRE output. The peaking units had decreasing capacity factors in the 13.3% and 18.8% scenario compared to the base case, but in the 25.0% scenario the capacity factors increased, as the increased wind penetration created a higher forecasting uncertainty and the peaking units compensated more for forecasting inaccuracies within this scenario. The inflexibility of the coal- and oil-fired power plants caused the capacity factors to be affected less by the increasing wind penetration compared to gas-fired power plants.

In Troy (2011), the effect of increasing wind penetration on the Irish power system was examined. Two versions of the Irish power system were examined: one with 7.55 GW peak demand and one with 9.6 GW peak demand. For each of the demand scenarios, three amounts of wind penetration were simulated: 15%, 29% and 43% for the 7.55 GW scenario and 11%, 23% and 34% for the 9.6 GW scenario. The remaining energy landscape consisted of natural gas-fired power plants (69%), coal-fired power plants (20%), other renewables (4%), hydropower (3%), pumped storage (3%) and tidal power (1%). The results for each scenario were expressed as capacity factor for a typical CCGT (400 MW) and coal plant (260 MW). These values were obtained by expressing results for all generators (e.g. OCGT, ADGT, CHP) per MW. The average results per MW were then obtained and multiplied by the 260 MW or 400 MW for a typical coal or CCGT power plant. The effect on the capacity factors of the two scenarios is presented in Table 5 and Table 6.

Table 5: 7.55 GW scenario (Troy, 2011).

Power plant	15% VRE	29% VRE	43% VRE
Typical CCGT	0.79	0.73	0.6
Typical coal	0.75	0.69	0.66

Table 6: 9.6 GW scenario (Troy, 2011).

Power plant	11% VRE	23% VRE	34% VRE
Typical CCGT	0.87	0.82	0.74
Typical coal	0.80	0.76	0.74

As the demand is higher in the 9.6 GW scenario, all capacity factors in this scenario were higher compared to the 7.55 GW scenario. There is however a significant difference between the capacity factor of CCGT and coal with increasing wind penetration, especially noticeable in the difference between the second highest scenario (i.e. 29% and 23% wind penetration) and the highest scenario (i.e. 43% and 34% wind penetration). The capacity factors of the CCGT in the highest scenario experienced a substantial decrease (-17.8% and -9.8%). This is explained by several factors. First, the high minimum output of CCGT due to emission restriction. When running as base load, CCGT achieve sufficient firing temperatures to allow CO to be oxidized into CO_2. The firing temperature does not reach a sufficient temperature when running in part load, resulting in increased CO emissions (Nag et al., 2008). Second, as the penetration of wind power increases, the need for spinning reserves (capacity on stand-by, ready to react to sudden changes caused by for example a power plant failure, sudden cloud-forming or windless period) increases. Due to the relative high efficiency of coal-fired power plants at part load levels and high minimum down time, coal plants are most suitable to act as spinning reserves at these high wind penetration levels. Therefore CCGTs were shut-down and displaced by wind generation.

The study of Göransson & Johnsson (2009) investigated the effect of increasing wind penetration in Denmark on the centralized fossil-fired power plants. This differs from the previously discussed studies where power plants were aggregated based on their type of fuel. The study simulated three scenarios: no wind, current wind (18%) and 34% wind. As Denmark is located in the Nodic power market, it has strong connections with neighbouring countries. In the study the import and export were therefore taken into account. The results indicated an increasing wind penetration caused a decrease in import (-13% for current wind and -18% for 34% wind) and an increase in export of electricity (+48% for current wind and +72% for 34% wind). This resulted in an overall increase in import + export. For most of the fossil-fired power plants, regardless of whether it was gas-fired or coal-fired, there was no consistency found in capacity trends. Only the most inflexible unit of Denmark, the Enstedtverket B3, showed a clear trend of decreasing capacity factor with increasing wind power capacity. This coal-fired power plant has the most expensive start-up and highest minimum load level, even though it has the lowest running costs of the system. The variations in wind power generation thus altered the dispatch order of the units, favouring units with more flexible properties to the unit with the lowest running costs. By increasing the exports by to Sweden, Norway and Germany by 44%, 91% and 100%, and decreasing the imports to these same countries by 22%, 18% and 13%, respectively, a large part of the 34% installed wind power was consumed without affecting the operation of fossil-fired power plants.

Conclusion

All studies showed that the fossil-fired full load hours decreased when increasing the VRE penetration. The largest decrease in full load hours found in gas-fired power plants was 27% when VRE penetration increased from 4% to 20%. In general, the decrease in full load hours of coal-fired power plants was found to be lower compared to gas-fired power plants. The highest decrease in full load hours of coal-fired power plants was found to be 12% with increasing VRE penetration from 15% to 43%. Import + export was found to be increasing when increasing the VRE penetration. Even though imports decrease at higher VRE penetration, the increase in export outweighed the decrease in import.

4.1.2 Efficiency

The reduction in full load hours of fossil-fired power plants is caused by cycling down to more frequent operating at part load levels or complete shut-down due to increased VRE. As discussed earlier, operating at part load levels and start-ups have a negative effect on the plant's energy efficiency. This negative effect differs per type of fossil-fired power plant and its age, therefore it is not possible to obtain general values for efficiency reduction. However, case studies are available to provide an indication of the variation in efficiency caused by operating at part load levels and start-ups. The two effects according to literature are treated in the following, separate two paragraphs.

Effect start-ups on efficiency

In Kumar et al. (2012), the amount of fuel per start-up for fossil-fired generation units was calculated. The amount of fuel combusted during start-up depends on the status of the power plant. If a power plant has been shut-down less than 8-12 hours ago, it is referred to as a hot start, between 12-48 hours for a warm start, and between 48-120 hours or even more a cold start (Lefton & Besuner, 2006). The longer the downtime, the highest the fuel consumption will be during start-up. In Table 7, multiple studies are listed in which the effect of higher penetration of wind power on the number of start-ups of fossil-fired power plants were simulated. These changes in start-ups were translated into an effect on the efficiency of the power plants by using start-up fuel consumption data from Kumar et al., (2012). In order to do so, the efficiency of coal-fired and CCGT power plants are assumed to be 40% and 52%, respectively, by own assumption. For each scenario, a range of efficiency effects are presented. The left limit within the range is if all start-ups are hot starts. The right limit is if all start-ups are cold starts.

Table 7: Efficiency effects in percentage points (pp) caused by start-ups according to literature.

Study	VRE	Type of plant	Delta start-ups per year	Effect efficiency
Troy (2011) - 7.55 GW scenario	15% → 43%	CCGT	50	[-0.2 pp, -0.5 pp]
		Coal	-5	[0.06 pp, 0.03 pp]
Troy (2011) - 9.5 GW scenario	11% → 34%	CCGT	55	[-0.2 pp, -0.5 pp]
		Coal	5	[-0.03 pp, -0.06 pp]
Göransson & Johnsson (2009)	0% → 34%	Coal	12	[-0.2 pp, -0.3 pp]
		CCGT	12	[-0.1 pp, -0.2 pp]

In the table above, the studies show that a significant increase in VRE did affect the amount of start-ups per year. However, due to the relatively high yearly generation of the coal-fired power plants and CCGTs (which are utilized as base load units), the relative impact on overall energy efficiency was found to be low, with a maximum efficiency effect of 0.5pp for gas-fired power plants and 0.06pp for coal-fired power plants.

Effect part load operation on efficiency

Operating at part load level affects the efficiency of a power plant. As previously mentioned, the effect of part load operation differs per type of power plant and year of construction. In Figure 3 and Figure 4 efficiency curves are presented that have been found in literature for natural gas and coal combustion technologies respectively. However, no literature was found on the effect of VRE on the frequency of part load operation. Therefore, the part load efficiency curves are only aimed at providing an indication of the range in which the efficiency may be affected by increased part load operation due to VRE intermittency. In Table 8 the meanings of the abbreviations used in the figures are listed. In Table 9 a summary is presented of the minimum part load efficiency, average efficiency and maximum full load efficiency of gas- and coal-fired power plants.

Table 8: Abbreviations of fossil-fired power plant technologies.

Abbreviation	Meaning
GT	Gas turbine
ST	Steam turbine
CHP	Combined heat and power
IGCC	Integrated gasification combined cycle
CC	Coal combustion
PCC	Pulverized coal combustion
SPCC	Supercritical pulverized coal combustion
RST	Retrofit steam turbine
CST	Conventional steam turbine
CCS	Carbon capture and storage

Table 9: Summary of part load efficiency literature results.

Abbreviation	Meaning	Min	Max	Type	Source
Gas	Low	16%	38%	Modern GT	(Welch & Pym, 2015)
	Average	45%	55%		
	High	38%	60%	Modern CCGT	(Dijkema et al., 2009)
Coal	Low	28%	47%	Modern IGCC	(Dijkema et al., 2009)
	Average	38%	43%		
	High	28%	47%	Modern IGCC	(Dijkema et al., 2009)

In Figure 3 below, load-efficiency curves of nine natural gas-fired power plants or technologies found in literature are presented.

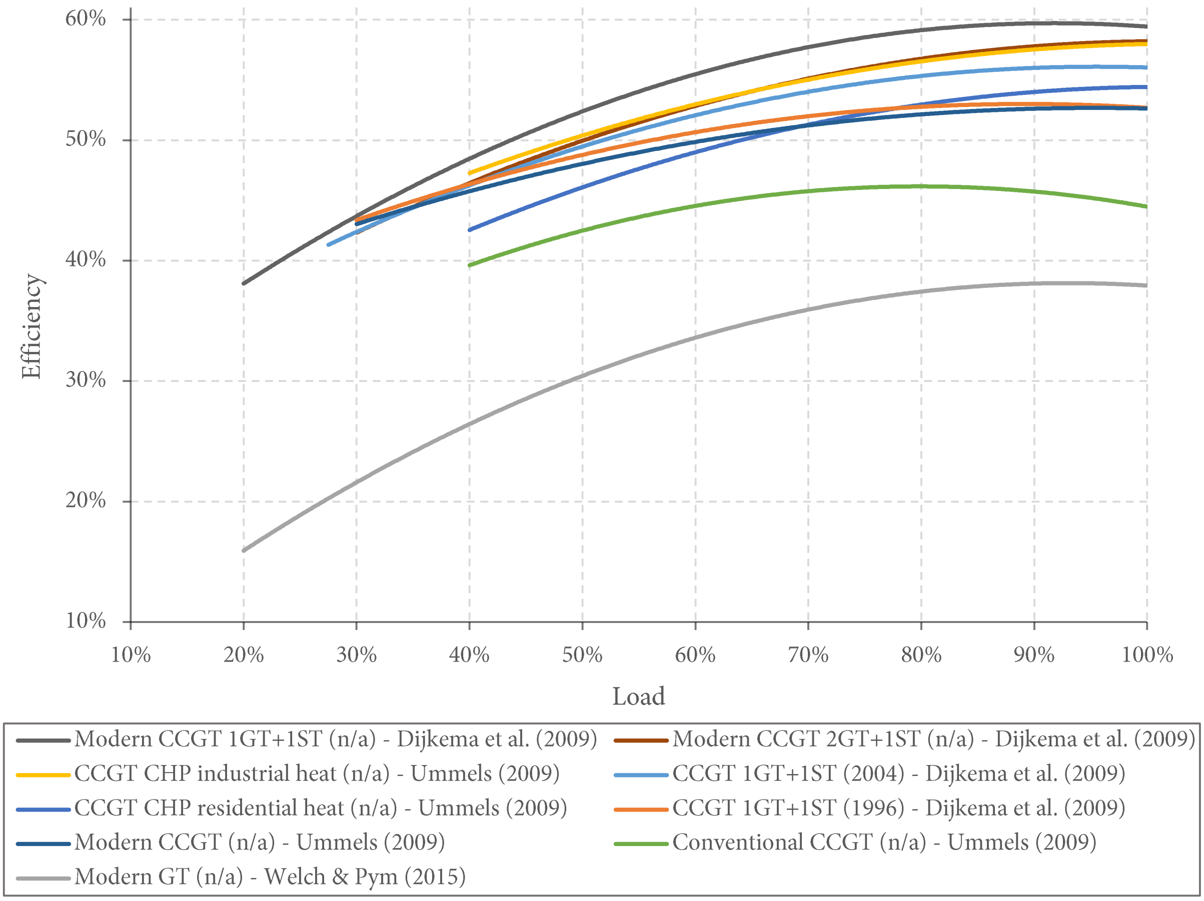

Figure 3: Part load efficiencies of gas-fired power plants in literature. Years of construction are in brackets.

Since data on individual, existing power plants is mostly kept inaccessible for public viewing due to competition purposes, most part load efficiency curves displayed in this figure are general technology data, and not power plant specific. For the natural gas-fired power plants, only the *CCGT 1GT+1ST (2004)* and the *CCGT 1GT+1ST (1996)* from Dijkema et al., (2009) represent existing power plants, namely the Rijnmond Energy power plant from InterGen and the EC-3 unit of the Eemscentrale owned by Engie Netherlands. The other seven load-efficiency curves are general technology curves and thus not power plant specific.

The seven most efficient natural gas-fired power plants and technologies are between full load efficiencies of 53% and 60%. The two modern CCGTs of Dijkema et al., (2009) are most efficient at full load with efficiencies of 60% and 59%, where the difference is caused by the amount of gas turbines. The need for flexibility in a landscape where VRE is increasing is noticeable in the minimum load of these two modern technologies, where the *Modern CCGT 1GT+1ST (n/a)* has a minimum operating level of as low as 20%. The two available CHP technologies differ from one another by the purpose for which the heat is used. The CHP plant where heat is used in industry is of higher part load and full load efficiency compared to a CHP plant where heat is used for residential heating (where heat is supplied to at lower temperatures). As the energy efficiency increases over time due to technology learning curves, it is expected that from the two available existing power plants mentioned in the previous paragraph, the most modern one (*CCGT 1GT+1ST 2004* versus *CCGT 1GT+1ST 1996*) is more efficient at full load. The final technology in this top seven is the *Modern CCGT (n/a)* from Ummels (2009). Then a small gap separates the *Conventional CCGT (n/a)* from Ummels (2009), which is of lower efficiency due to its older age. Finally, the lowest load-efficiency curve represents a small (50 MW), modern gas turbine from Welch & Pym (2015). Gas turbines are used as peaking units and are characterized by their high cycling capacity. This results in a lower efficiency compared to base load (combined cycle) units. As these units need to be on standby often, low minimum load levels are required, as indicated by the 20% in the figure.

More importantly than identifying the difference in full load efficiencies and minimum load levels, is looking at the range of efficiency between a power plant's minimum and full load operation. This gives an indication in what the efficiency difference can be between natural gas-fired power plants in a countries with high, medium or low VRE penetration. The largest differences were found in the *Modern CCGT 1GT+1ST (n/a)* and the *Modern GT (n/a)*, with an efficiency range of 23pp. These two power plants are designed for flexible operation with minimum load levels of 20% to be able to react quickly when sudden changes in VRE output occur. In countries where the penetration of VRE is high, the overall efficiency of natural gas-fired power plants may be lower than in countries with low penetration VRE, due to more part load operation of these flexible, but also inflexible power plants. The other natural gas-fired power plants show variations of between 17pp and 10pp between minimum and full load. The only exception is the *Conventional CCGT (n/a)* which only has a difference of 6pp efficiency between minimum and full load, but is at full load (45%) even less efficient than almost all of the other more modern CCGTs.

In Figure 4 below, the load-efficiency curves of the nine coal-fired power plants or technologies found in literature are presented.

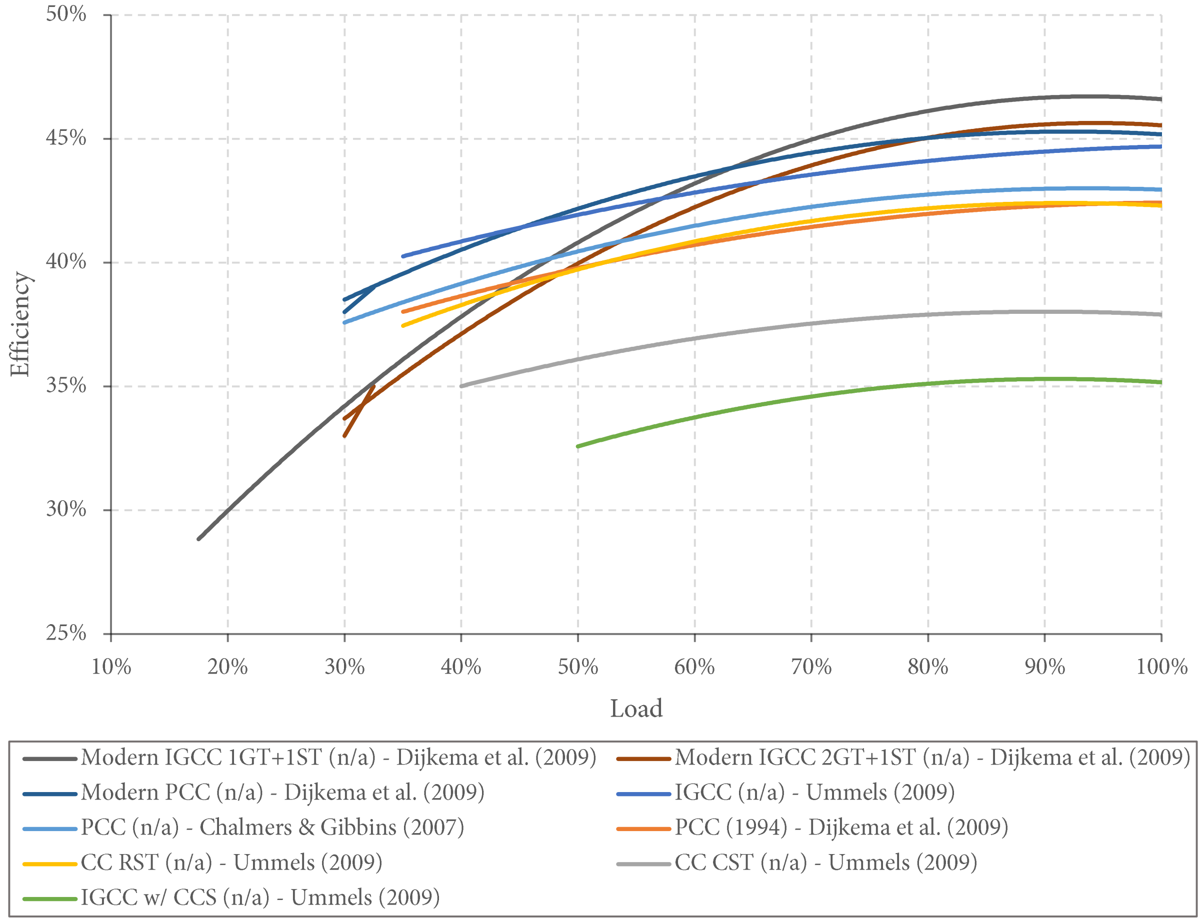

Figure 4: Part load efficiencies of coal-fired power plants in literature. Years of construction are in brackets.

Similar to the natural gas-fired power plants, most of the data represent general technologies and are not power plant specific. Only the *PCC (1994)* from Dijkema et al., (2009) represents an existing power plant, namely the Hemweg-8 from electric utility Nuon. The remaining eight load-efficiency curves are general technology curves and not power plant specific.

The seven most efficient coal-fired power plant curves are between 43% and 47% efficiency at full load. The two most efficient power plants are the *Modern IGCC 1GT+1ST (n/a)* and the *Modern IGCC 2GT+1ST (n/a)* which both make use of the gasification process, where a gas mixture of CO, H_2 and CO_2 is obtained from the coal and combusted, instead of direct combustion of coal. Where most coal-fired power plants have minimum load levels of 30% or higher, the *Modern IGCC 1GT+1ST (n/a)* has a minimum load level of 18%, which improves its flexibility properties and would make it more suitable in a landscape with high penetration VRE. The difference between the two most efficient power plants mentioned above and the *Modern PCC (n/a), IGCC (n/a), PCC (n/a)* and *PCC (1994)* is little (1pp-4pp). This means that the pulverized coal combustion technology, where the coal is first pulverized into a powder-like substance before combusted, is close to the gasification technology in terms of efficiency, with just a small advantage of the (modern) IGCC power plants over the (modern) PCC power plants. A gap of 5pp efficiency at full load is identified between the technologies mentioned above and the *CC CST (n/a)*, representing a coal-fired power plant with a conventional steam turbine. This traditional technology cannot match the efficiencies of the pulverized and gasification technologies. However, when the steam turbine is retrofitted in the *CC RST (n/a)*, the efficiency increases and closes the gap to the efficiency of the least performing PCC power plant. Finally, the lowest full load efficiency is reached by the *IGCC w/ CCS (n/a)*, where the lower efficiency is caused by the addition of CCS technology, which is known to have a negative effect on plant efficiency (e.g. Goto et al., 2013).

When looking at the difference between minimum load efficiency and full load efficiency of the technologies, it can be identified that the largest range is found in the two most efficient technologies at full load: the *Modern IGCC 1GT+1ST (n/a)* and the *Modern IGCC 2GT+1ST (n/a)*, with a range of 19pp and 13pp, respectively. The highest range of 19pp is primarily caused by the low minimum load level of 18%, as the efficiency decrease between load levels 18% and 30% (the minimum load level of most other technologies) is as high as 6pp. The rest of the technologies have substantially lower ranges, varying from 3pp to 8pp, indicating the relatively small energetic impact of part load operation in coal-fired power plants.

Natural gas-fired power plants vs. coal-fired power plants

When comparing the load-efficiency curves of natural gas-fired power plants (Figure 3) with coal-fired power plants (Figure 4), multiple differences are identified. First, the average full load efficiency of the natural gas-fired power plants is higher than that of coal-fired power plants, 53% versus 43%. Even the average minimum load efficiency of base load natural gas-fired power plants (i.e. excluding the efficiency of the peaking unit *Modern GT*) is almost as high as the average full load efficiency of coal-fired power plants, namely 42%. Second, the average efficiency difference between minimum load and full load level of natural gas-fired power plants is twice as high as that of coal-fired power plants, 14pp versus 7pp. So part load operation of coal-fired power plants has a relatively smaller impact on its energetic performance than that of natural gas-fired power plants. However, when taking into consideration the previously mentioned observation, often operating natural gas-fired power plants at minimum load levels is still more energy efficient than operating a coal-fired power plant at full load level. So solely from an energetic point of view, without taking into consideration the costs, it would be more efficient to operate the natural gas-fired power plants in this case. The third and final observation when comparing the two figures is that in both graphs the minimum load levels in the most modern technology decreases. This would be beneficial in a landscape where the share of VRE increases and more flexibility is demanded from fossil-fired power plants.

Figure 3 and Figure 4 illustrate the effect of real-time part load operation on plant efficiency. However, the efficiency averaged over a year is dependent on how often which level of part load operation was maintained. This data is not available, but the figures were used to provide an indication of what the range in efficiency can be for each technology.

Conclusion

The maximum efficiency effect caused by increased start-ups was found to be 0.5 pp in CCGTs, when the VRE penetration was increased from 11% to 34%. The efficiency effect on coal was found to be lower, as in the studies gas-fired power plants are mainly used for compensating VRE output. The highest effect on coal-fired power plant's efficiency was found to be 0.06 pp when VRE penetration increased from 11% to 34%.

The effect of part load operation on the efficiency of fossil-fired power plants was found to be potentially higher. For gas-fired power plants the highest range was found in a modern CCGT, ranging from 38% efficiency at 20% load and 60% efficiency at full load. The average gas-fired power plants ranged from 45% efficiency at 40% load to 55% at full load. The highest range found in coal-fired power plants ranged from 29% efficiency at 20% load to 45% efficiency at full load. The average coal-fired power plants ranged from 38% efficiency at 35% load to 43% efficiency at full load. However, no literature was found on the effect of VRE on the frequency of part load operation. Therefore, the abovementioned part load efficiency curves are only aimed at providing an indication of the range in which the efficiency may be affected by increased part load operation due to VRE intermittency.

4.2 Shares of variable renewable electricity in EU member states

In Figure 5, the VRE penetration of the European Union is plotted from 1990-2014. In Figure 6, the same trend is plotted but for the individual EU member states. The EU member states Czech Republic, Latvia, Lithuania and Luxembourg have been excluded from this research, as capacity data in (Platts, 2011) was found to be incomplete (i.e. not all power plants were included, leading to unrealistically high full load hours of 15,000 and higher). From this point onwards, when referred to European Union, the abovementioned member states are excluded.

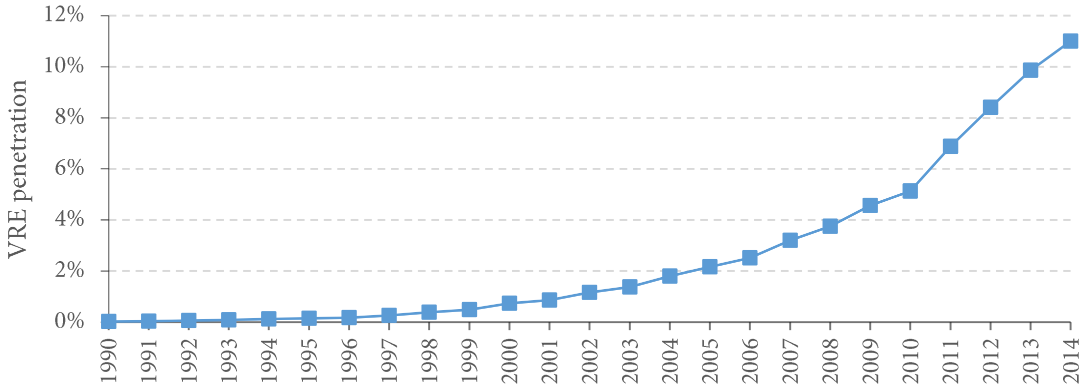

Figure 5: VRE penetration trend European Union.

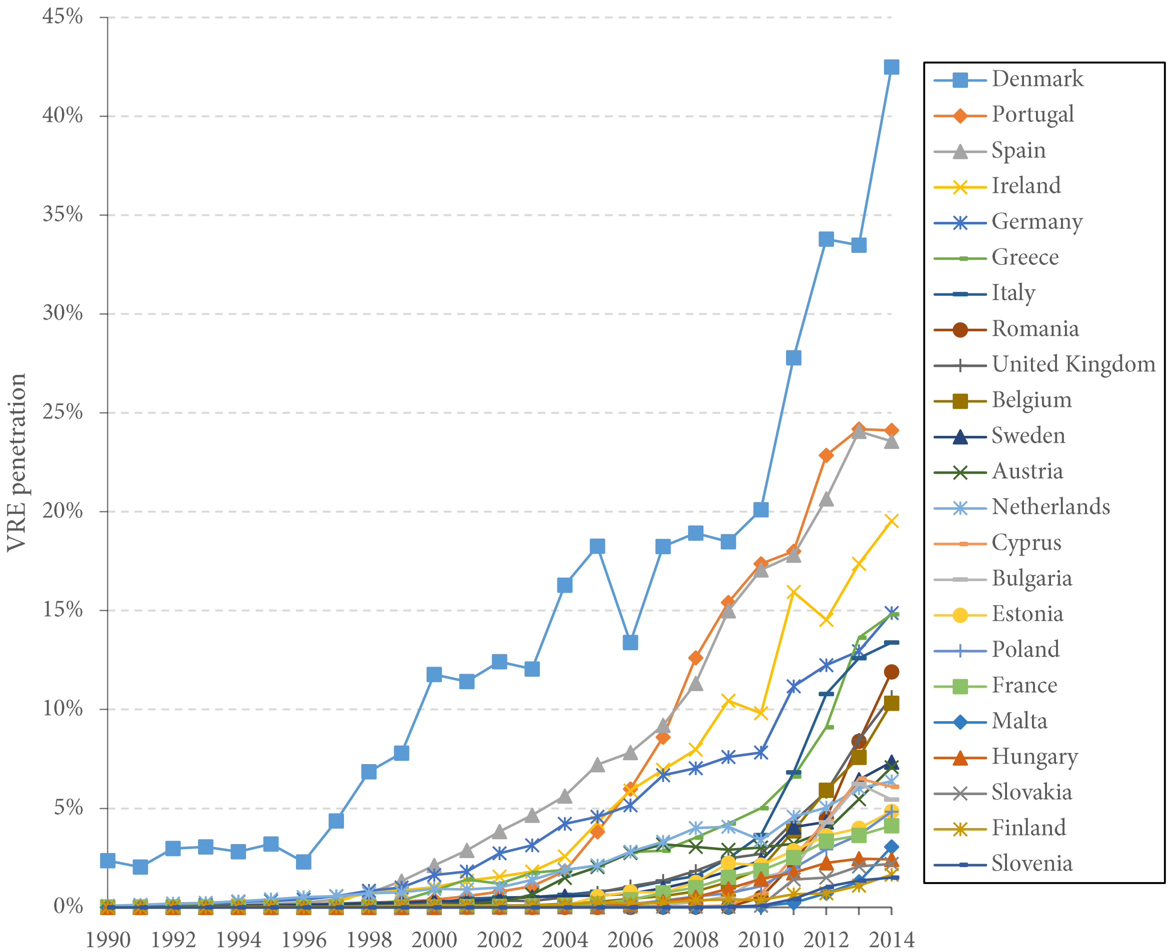

Figure 6: VRE penetration trends in EU member states.

The VRE penetration in the European Union has grown from 0% in 1990 to 11% in 2014, as shown in Figure 5. As previously mentioned in the introduction, the distribution of VRE is not evenly spread over the EU member states. This is made visible by Figure 6. Looking at the most recent year, 2014, the penetration of VRE ranged from 1.5% in Slovenia to 42.5% in Denmark. Three groups were determined based of the magnitude of VRE penetration, presented in Figure 7. First, the red group with low VRE penetration (0%-7.5%) consists of Sweden, Austria, Netherlands, Cyprus, Bulgaria, Estonia, Poland, France and Malta, Hungary, Slovakia, Finland and Slovenia. Then the yellow group with medium VRE penetration (7.5%-15%) is identified, consisting of Germany, Greece, Italy, Romania, United Kingdom and Belgium. Finally the last group, in green, with high VRE penetration (15%+) consisting of Denmark, Portugal, Spain and Ireland. From this point onwards the three groups will be referred to as *VRE-low*, *VRE-medium* and *VRE-high*.

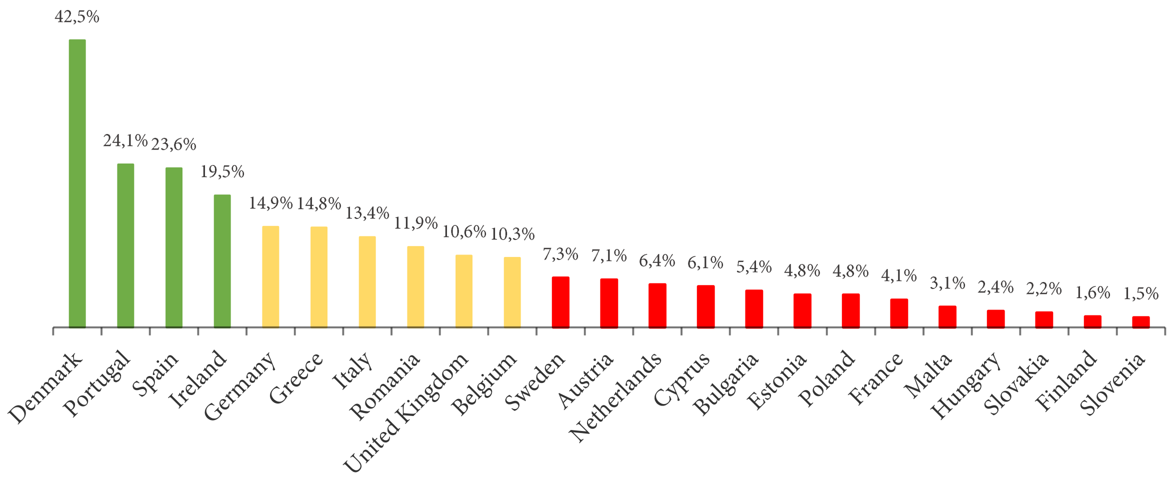

Figure 7: VRE penetration of EU member states in 2014.

4.3 VRE-high

The VRE-high group consists of Denmark, Ireland, Portugal and Spain. Averaged over the timeframe 1990-2014, the country's individual shares of the total fossil electricity generation are 10% for Ireland, 13% for Portugal, 15% for Denmark and 61% for Spain. The individual results for Spain will therefore weigh the highest in the results of the VRE-high group. Due to this high dominance, individual results of Denmark, Ireland and Portugal are presented in Appendix C.

4.3.1 Full load hours

The total electricity generation in VRE-high increased in the period 1990-2006 from 221 TWh to 422 TWh, as displayed in Figure 8. The total electricity generation then levelled and in 2009, the year after the start of the financial crisis, the total electricity generation experienced its largest decrease of over 4%. Aside from an increase in 2010, total electricity generation decreased since 2009 onwards. The decrease in total electricity generation from 2009, combined with the steady increase in VRE generation until 97 TWh in 2014, caused the fossil-fired capacities to lower their combined electricity output. This was mainly done by coal and gas, which declined by approximately the same amount from 2008-2010, 30 TWh and 24 TWh. However, in 2011, coal generation increased while gas continued to decline. This was partly caused by a dry period in Portugal and Spain, resulting in a lower output of hydropower, categorized under other renewables. In 2011, hydropower output decreased by 27% and 28% in Portugal and Spain, respectively, and in 2012 by 45% and 26%. Coal was favoured over gas in this recent period due to financial motives. The development of new extraction technologies enabled unconventional gas supplies to be exploited in North America, altering natural gas production and trade globally. The shift of North America to natural gas, caused coal suppliers from and to North America to look for new markets for their excess coal supply, primarily in Europe (Greenpeace, 2013). The low price at which the coal was sold in Europe, combined with a low EU-ETS carbon price, caused coal to become more favourable than the relatively expensive natural gas.

Nuclear power generation remained more or less constant for the whole period of 1990-2014. Oil production, the lowest source of electricity generation, decreased at an approximately constant rate from 2002 onwards, mainly as it is an outdated fuel type for electricity generation and most of the oil-fired power plants were old and being phased out.

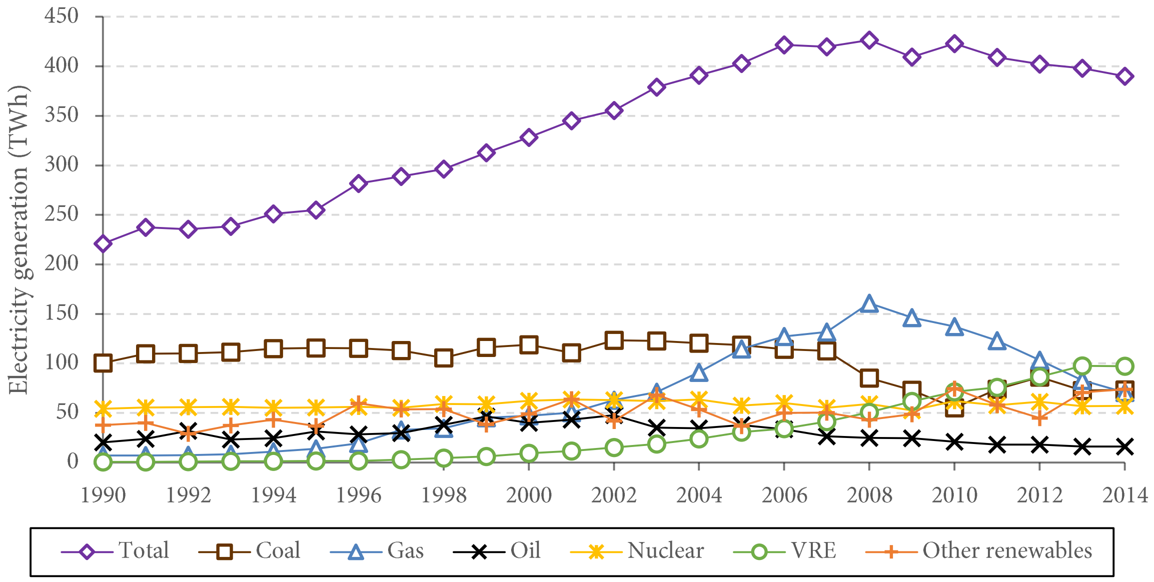

Figure 8: Electricity generation trends by source in VRE-high.

As shown in the causal diagram in Figure 2, the fossil-fired full load hours are determined by total electricity generation, presented in Figure 8 above, VRE penetration and installed non-VRE capacity. The development of all three factors are presented in Figure 9 below and the trends in full load hours of coal, gas, oil and total fossil, combined with the trend in VRE penetration are presented in Figure 10.

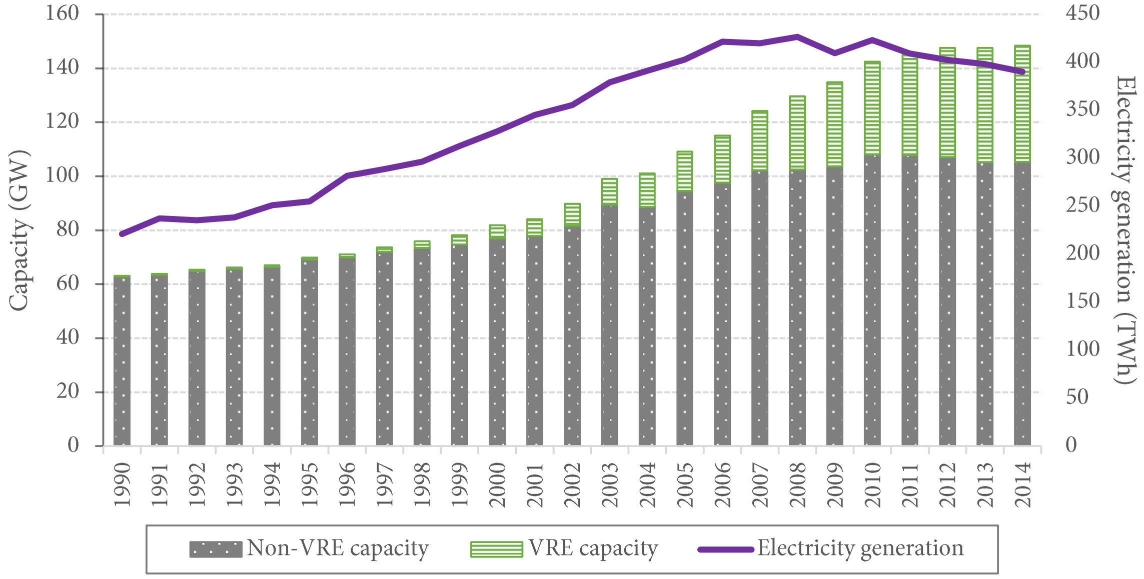

Figure 9: Non-VRE capacity, VRE capacity and total electricity generation trends in VRE-high.

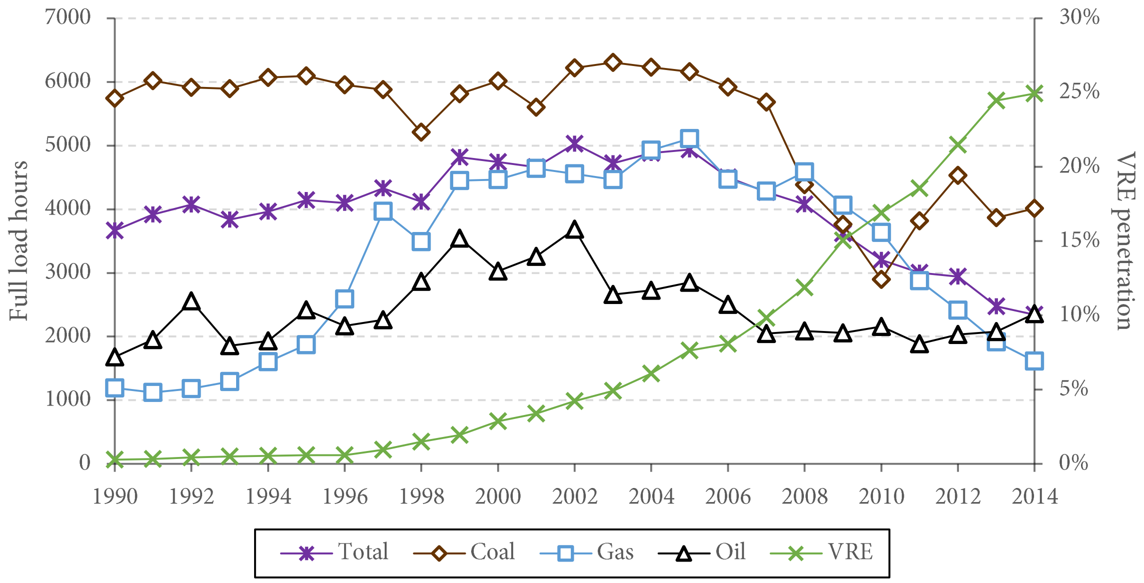

Figure 10: VRE and full load hour trends in VRE-high.

As identified from Figure 8, total electricity generation rose between 1990-2006 from 221 TWh to 422 TWh, an increase of 82%. Within this period, the total installed capacity, consisting of non-VRE and VRE capacity, increased at the same rate. The non-VRE capacity increased from 63 GW to 98 GW and VRE capacity from 0 GW to 17 GW, leading to a total capacity increase of 83%. While the percentage increase of both the total electricity generation and total capacity are almost identical, the full load hours increased by 35% from 3,665 in 1990 to 4,935 in 2005. This was caused by the relatively higher share of VRE capacity in the total capacity. Since VRE installation have lower capacity factors than fossil-fired installation, 1 MW of VRE installation can produce less electricity than 1 MW non-VRE capacity. The capacity factor for wind is around 30% (EWEA, 2016) and for PV around 25% (EIA, 2016), while the capacity factor for fossil-fired power plants can be as high as 85% (Tidball et al., 2010). Therefore, due to the higher share of VRE capacity in the total capacity, the fossil full load hours increased within this period.

In the period 2006-2010, total electricity generation levelled around 422 TWh, besides the dip in 2009 caused by the previously discussed effect of the financial crisis. Within this period, the non-VRE capacity increased from 98 GW in 2006 to 108 GW in 2010, a 10% increase. Most of this increase consisted of new gas-fired capacity in Spain. A large number of new CCGTs were installed within these years, for example the 1,200 MW El Fangal in Cartagena (2007), the 800 MW Escombreras 6 (2007) and the 850 MW Bésos 5 in Barcelona (2010). The VRE penetration increased by 100%, from 17 GW in 2006 to 34 GW in 2010. The levelling total electricity generation combined with an increasing non-VRE capacity and VRE capacity had a decreasing fossil full load hours trend as a result. The full load hours decreased by 29% from 4,502 in 2006 to 3,205 in 2010.

In the most recent period, from 2010-2014, the total electricity generation decreased from 423 TWh in 2010 to 390 TWh in 2014, a decrease of 8%. Within this period, the non-VRE capacity decreased as well, by 3% from 108 GW in 2010 to 105 GW in 2014, mostly caused by the mothballing (i.e. temporary taking out of production of a power plant) of coal-fired power plants in Denmark. The VRE capacity experienced its largest increase within this period from 34 GW in 2010 to 43 GW in 2014, an increase of 26%. The developments in total electricity generation and non-VRE capacity have a neutralizing net effect. It is not possible to precisely calculate what the net effect of the developments of these two trends would be on fossil full load hours, but as the two developments neutralize each other, the total effect on fossil full load hours should be at least less than 8% (i.e. the effect of a decreasing total electricity generation on the fossil full load hours). However, the fossil full load hours decreased from 3,205 in 2010 to 2,344 in 2014, a decrease of 27%. Therefore, the greater part of this increase can be allocated to the 26% increase in VRE capacity.

When breaking down the total fossil fuel trend into the individual fossil fuels, it can be identified that the increasing total fossil full load hours from 1990-2005 is allocated to gas-fired power plants. In 1990 gas-fired power plants consisted of only 13%, 25%, 3% and 15% of total fossil capacity in Denmark, Ireland, Portugal and Spain, respectively. Gas-fired capacity consisted mostly of small gas turbines used for as peaking units, especially in Portugal where the total gas-fired capacity from 1990-1997 consisted only of two 50 MW gas turbines. A large share of the decreasing full load hours from 2006-2014 can also be allocated to gas-fired power plants, as the full load hours decreased from 5,108 to 1,616 within this period. As mentioned earlier, natural gas prices were higher than coal within that period, making coal-fired electricity generation more favourable (Greenpeace, 2013). The full load hours of coal were found to be more or less constant, besides two small dips in 1998 and 2001, around an average of 6,000 full load hours, until 2005. The full load hours then started decreasing slightly until a large 23% decrease in 2008. The decrease in full load hours in 2008 complies with the decrease in coal generation presented in the previous Figure 8. The full load hours of coal between 2007-2010 decreased from 5,681 to 2,897. The generation by the relatively cheap coal then increased again and was around 4,000 full load hours in the most recent years 2013 and 2014. The full load hours of oil-fired power plants were significantly lower compared to coal and gas. The oil full load hours rose from 1990-2002 from 1,682 to 3,687 and then gradually decreased to 2,357 in 2014.

According to the causal diagram in Figure 2, the magnitude of import + export is influenced by VRE penetration. There is a rising trend in import and exports as the VRE output increases, as can be identified from Figure 11. The import + export varies between 8% and 18% of total electricity generation. The correlation between the trends of import + export and VRE generation was found to be very strong at 0.89, as can be seen in Figure 51 in Appendix D. Even though this reflects a very strong dependency, a note is made that the results are biased. The amount of import + export does most likely not only increase due to higher VRE output but increases in general, because the capacities of interconnections between countries are expanded over time. Electricity imported or exported is not necessarily excess renewable electricity but can be non-renewable electricity transported for financial motives.

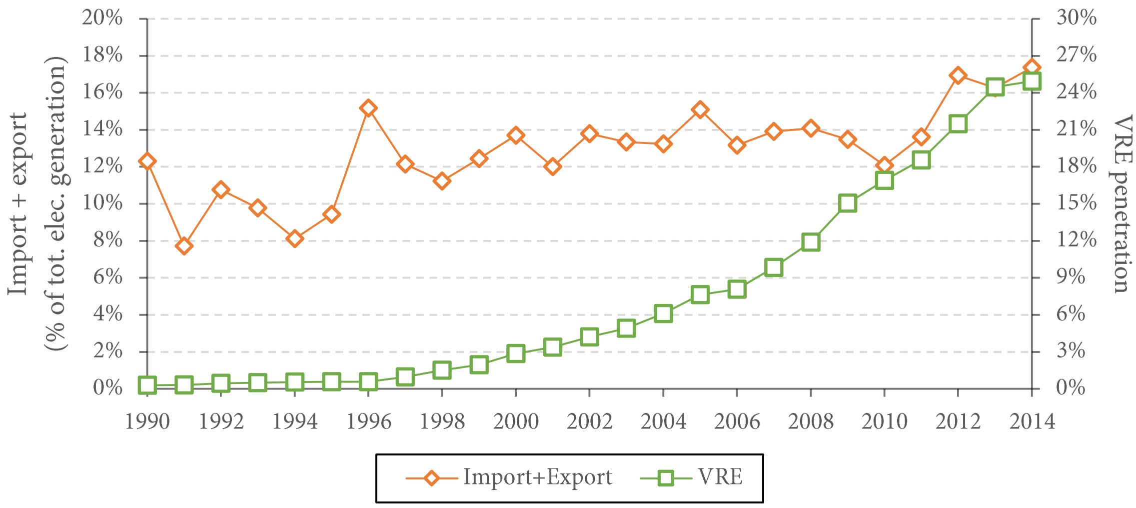

Figure 11: VRE and import + export trends in VRE-high.

The highest relative import + export compared to its total electricity generation is Denmark. Denmark is part of the Nordic Power Pool together with Sweden, Finland, Norway and Iceland, and has high capacity cross-border power connections. To further investigate what the effect of VRE on import + export may have, and import + export in its turn on fossil full load hours, these three trends in Denmark are presented in Figure 12. The very strong correlation of 0.89 found between the VRE penetration and import + export in VRE-high is also visible in the trends of Denmark, which both have an increasing trend. Within this figure, even small peaks and dips in VRE penetration seem to correlate with peaks and dips in import + export. Dips and peaks in both trends are visible in for example 2005-2007, 2012 and 2014. The import + export seems to have a negative relationship with fossil full load hours. In 2005 and 2012 for example the share of import + export of the total electricity generation reached local peaks, while fossil full load hours reached local minimums. These peaks in import + export were dominated by imports. The net imports within these years were 1.37 TWh and 5.21 TWh for 2005 and 2012, respectively. The positive net imports displace electricity otherwise produced by fossil-fired power plants, thus lowering their average full load hours.

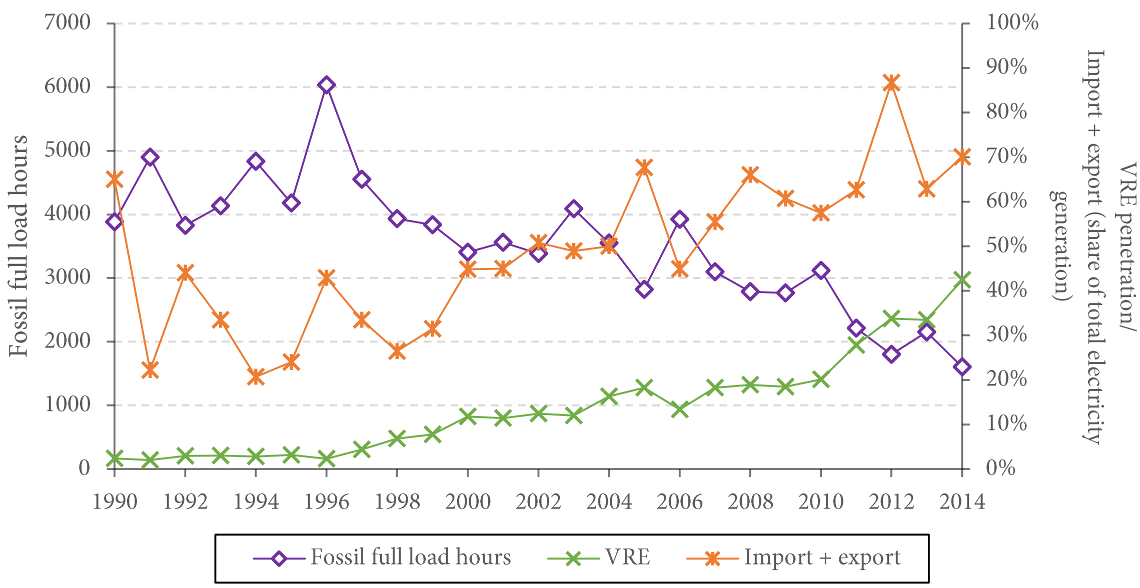

Figure 12: Fossil full load hour, VRE and import + export trends of Denmark.

4.3.2 Efficiency

In Figure 13, the trends of energy efficiency and average year of commission for coal-fired power plants in VRE-high are presented. Coal efficiency was 38% at the start of the timeframe in 1990 and fluctuated around this height until a peak was reached in 2008 at 40% efficiency. This 40% efficiency was maintained until 2010. From this point onwards, a large decrease in efficiency is visible until 38% in 2014. In Figure 14, the correlation between the trends of efficiency and average year of commission are presented. The correlation is very weak with an R^2 value of 0.28. This weak correlation is caused by the small amount of new coal-fired capacity that was added within the timeframe. Two clear increases in average year of commission can be identified: 1998 and 2007. In 1998 the increase was caused by the commissioning of the 535 MW Litoral de Almería power plant in Spain. The increase in average year of commission in 2007 was caused by the commissioning of the 550 MW Lada power plant in Langreo, Spain. The changes in efficiency within the timeframe were also relatively small as fluctuations were for the larger part between 38% and 40%. So even though the calculated correlation is very weak, the actual correlation may be high as the trends show that little new capacity was installed and that the efficiency remained fairly constant. The small deviations in energy efficiency may be caused by either uncertainties in statistics or could have been the effect of VRE intermittency. The decrease in efficiency from 2010-2014, seems to be too large to be allocated to uncertainties in statistics. Even though no data is available on average year of commission within the last year of the timeframe, in the worst case scenario no new coal capacity was installed. In that case, the efficiency would more or less have to remain constant, neglecting small efficiency decreases due to deterioration of machinery. However, the efficiency decreased from 40% in 2010 to 38% in 2014, while the VRE penetration increased from 17% to 25% within this period. Therefore, it is likely that this efficiency decrease was caused by increased start-ups and part load operation of coal-fired power plants due to the increased VRE penetration.

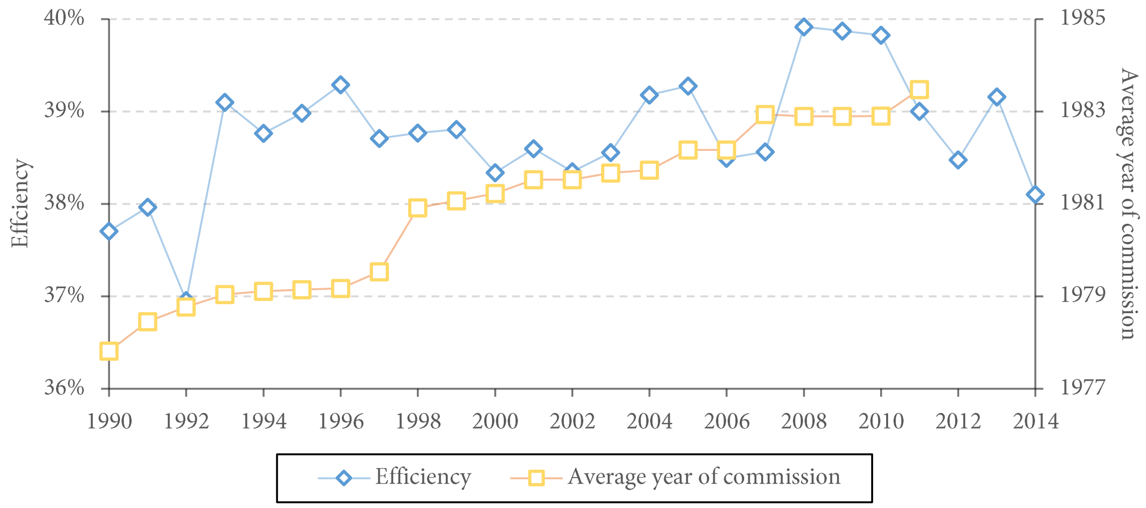

Figure 13: Efficiency and average year of commission trends of coal-fired power plants in VRE-high.

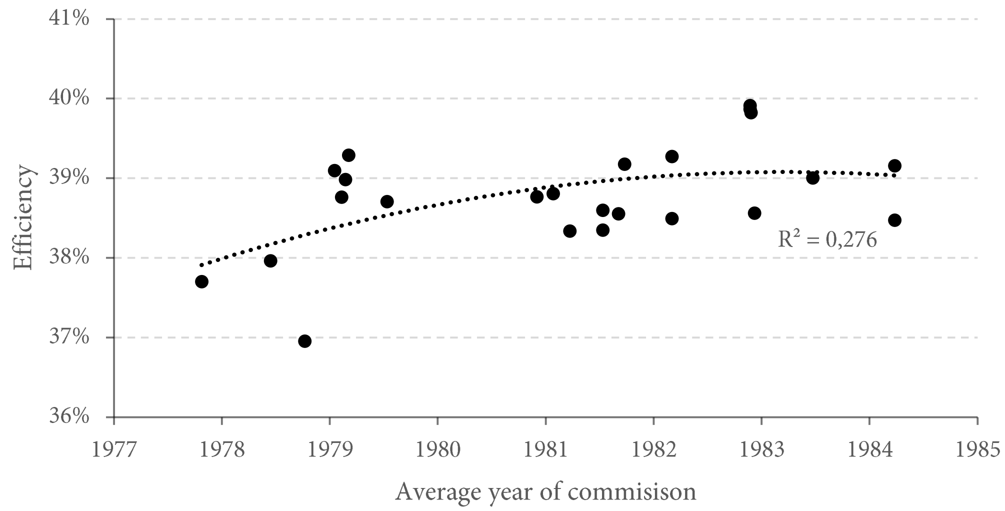

Figure 14: Correlation average year of commission and efficiency of coal-fired power plants in VRE-high.

In Figure 15, the trends of energy efficiency and average year of commission of gas-fired power plants are plotted. In Figure 16 the correlation is calculated, which shows a very strong dependency of efficiency on the average year of commission, with an R^2 value of 0.92. The higher correlation between these two trends, compared to the trends in coal-fired capacity, is caused by the rapid installation of new gas-fired capacity, which resulted in a substantial efficiency increase. The average efficiency of gas-fired power plants was 40% in at the beginning of the timeframe in 1990. A rapid increase is identified between 1997-2005, where the efficiency increased from 41% to 55%. This increase was caused by the increase in average year of commission, from 1984 in 1997 to 1995 in 2005. Within this period 15.2 GW of gas-fired capacity was installed, most of which CCGTs. The largest amount of capacity was installed in Spain: 10.7 GW. From 2005-2011 the efficiency of gas-fired power plants levelled around 54%, while still new gas-fired capacity was installed, resulting in an increase in average year of commission from 1995 to 2003. According to Graus et al. (2008), the average efficiency of gas-fired power plants under construction or planned in the period 2005-2015 in the EU was 59%. This indicates that the levelling of energy efficiency between 2005-2011 was not caused by power plants reaching their state of the art, maximum efficiency, but likely by gas-fired power plants being forced into inefficient operation (i.e. increased start-ups and part load operation) due to the intermittency of VRE generation. For the latest period, between 2011-2014, the efficiency of gas-fired power plants even decreased from 54% to 52%. Even though no data on average year of commission was available, in the worst case scenario no new gas-fired power plants were installed and the efficiency would remain more or less constant. It is therefore likely that the efficiency decrease within these last three years was the result of VRE intermittency.

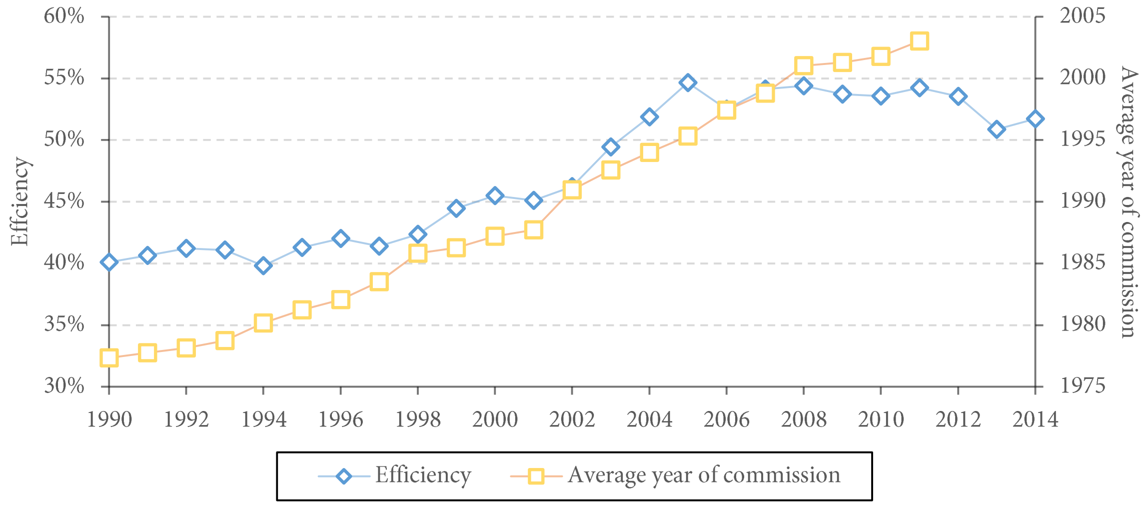

Figure 15: Efficiency and average year of commission trends of gas-fired power plants in VRE-high.

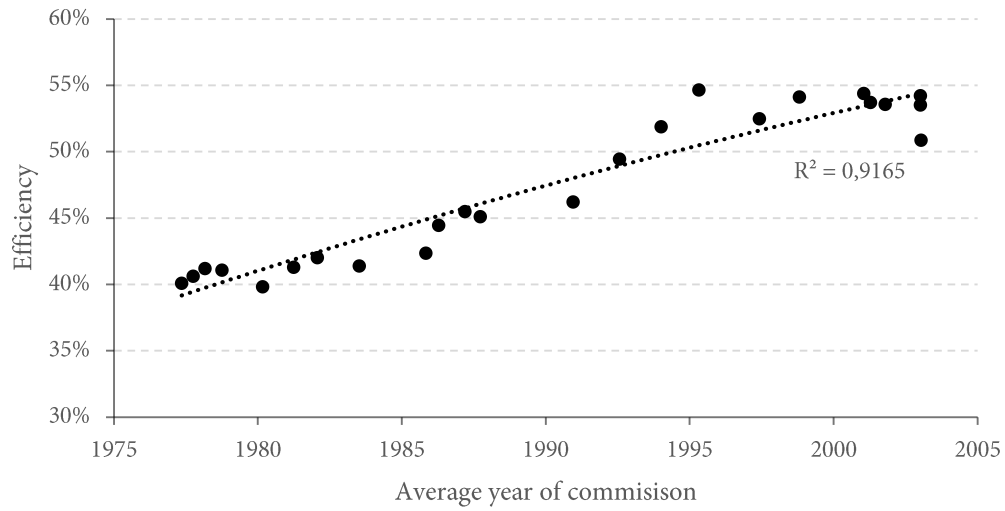

Figure 16: Correlation average year of commission and efficiency of gas-fired power plants in VRE-high.

Conclusion

In the period 2010-2014, a decrease in fossil full load hours was found that is for the larger part allocated to an increase in VRE penetration. Even though a decrease in fossil full load hours was found between 2006-2010 as well, the 10% increase in non-VRE capacity may be of larger influence on this decrease than the increase in VRE penetration within this period. From 2010-2014 however, the non-VRE capacity decreased by 3%, while the total electricity generation decreased by 8%. The neutralizing effect of these two developments would results in a net effect on full load hours of at least lower than the 8% decrease in electricity generation. The full load hours were found to be decreasing by 27% from 3,205 to 2,344, while VRE capacity increase by 26% from 34 GW to 43 GW, representing a VRE penetration increase from 17% to 25%. Therefore, the decrease of 861 full load hours between 2010-2014 is allocated for the greater part to the increase in VRE penetration.

The import + export was found to be increasing as the VRE output increased as well, and a strong correlation was found between these two factors. However, this result is biased, as import + export capacities between neighbouring countries have been expanded over time, as well as the VRE penetration, independently of each other.

Finally, the energy efficiency was found to be very strongly dependent on the average year of commission. In the latest years, from 2010-2014 coal efficiency decreased from 40% to 38%, which was most likely the results of VRE intermittency. Gas efficiency increased in the first period, caused by the rapid installation of new gas-fired capacity, until 2005. From 2005-2011 the gas efficiency levelled around 54% while the average year of commission increased. From 2011-2014 the gas efficiency decreased from 54% to 52%, most likely the effect of VRE intermittency.

4.4 VRE-medium

The VRE-high group consists of Belgium, Germany, Greece, Italy, Romania and the United Kingdom. Averaged over the timeframe 1990-2014, the country's individual shares of the total fossil electricity generation are 3% for Belgium, 4% for Romania, 5% for Greece, 22% for Italy, 28% for the UK and 39% for Germany.

4.4.1 Full load hours

Similar to VRE-high, the total electricity generation in VRE-medium, presented in Figure 17, experienced an increase within the first period of the timeframe, between 1990-2007. In this period, the total electricity generation increased from 1,250 TWh to its highest point of 1,565 TWh. From 2008-2014 the total electricity generation decreased, apart from the recovery year 2010, after the dip of the financial crisis, from 1,565 TWh to 1,435 TWh. The reduced total electricity generation is mostly compensated by reduced electricity generation from gas, and to a lesser extent from nuclear and oil. Not only did these three generation types compensate for lower total electricity generation, but also for the increase in other renewables and especially VRE generation, which increased from 114 TWh in 2011 to 190 TWh in 2014. Coal-fired electricity generation was more or less constant from 1990-2007. From 2007-2009 coal experienced a decrease from 543 TWh to 457 TWh which is in line with the lowering total electricity generation. Then, as gas continued to decline, coal-fired power plant generation increased again from 2010, most likely due to the same reason mentioned in the high VRE group: a low coal price.

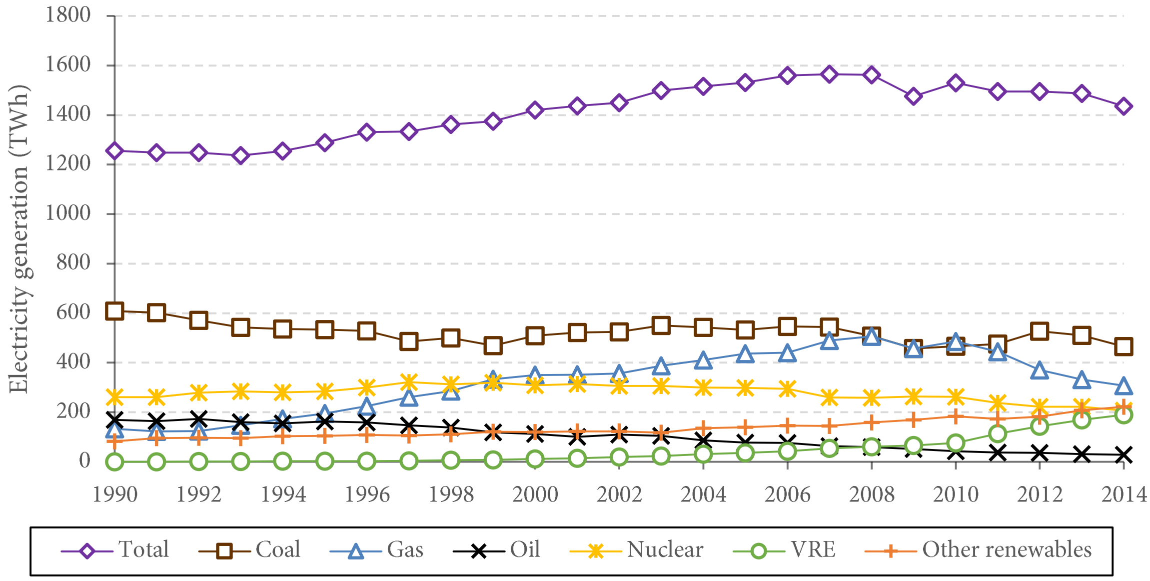

Figure 17: Electricity generation trends by source in VRE-medium.

In Figure 18 below the trends in non-VRE capacity, VRE capacity and total electricity generation are plotted and in Figure 19 the full load hours trends.

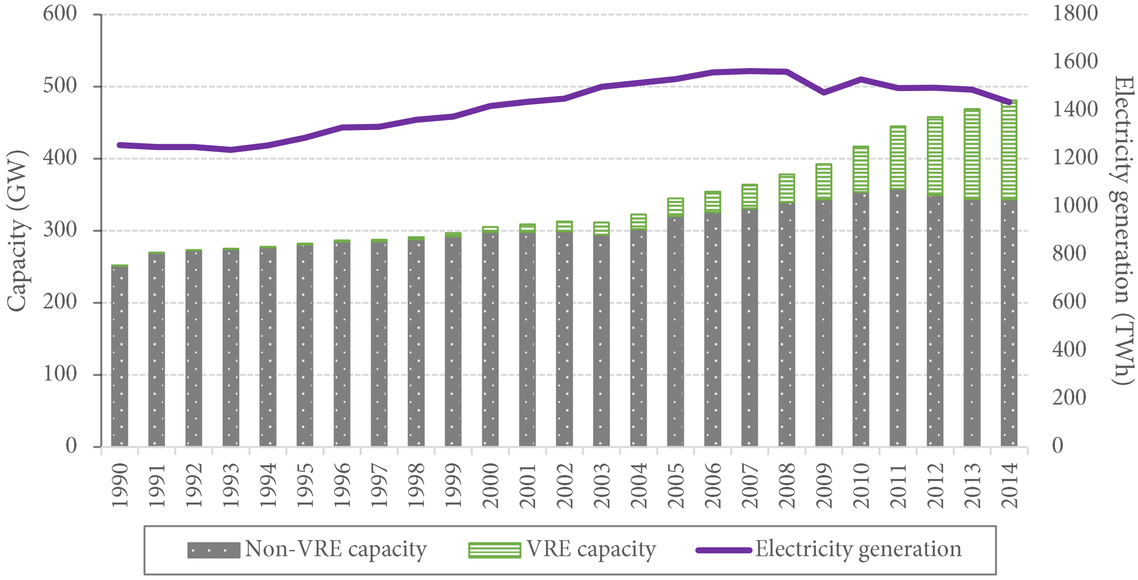

Figure 18: Non-VRE capacity, VRE capacity and total electricity generation trends in VRE-medium.

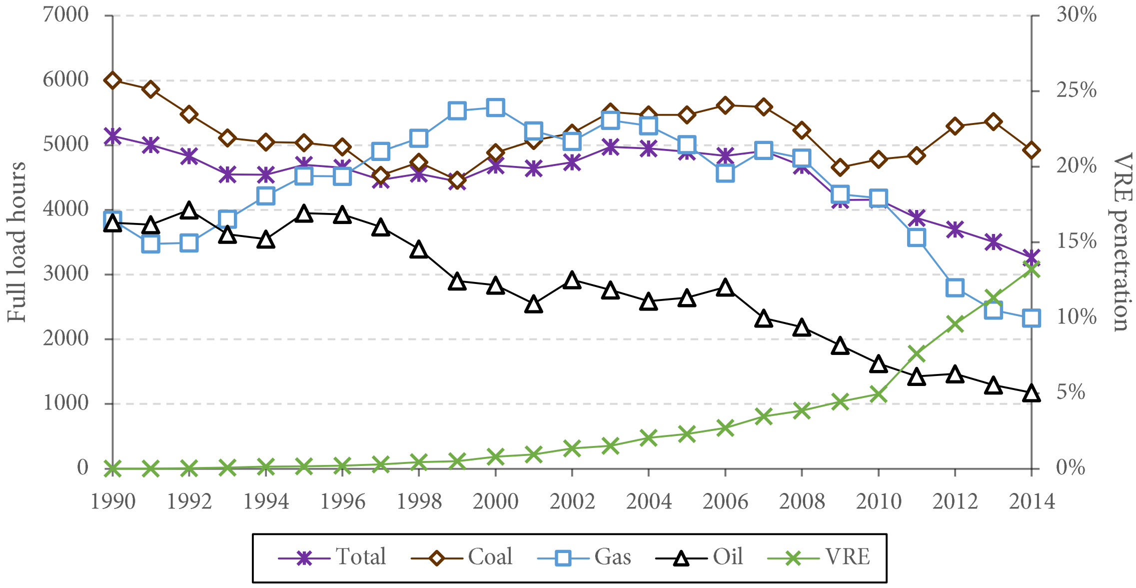

Figure 19: VRE and full load hour trends in VRE-medium.

As can be identified in Figure 19, the full load hours decreased in the first period 1990-1994 from 5,142 to 4,546. In Figure 18, it can be identified that this was caused by a levelling total electricity generation of 1,255 TWh combined with an increasing non-VRE capacity from 251 GW to 277 GW. The largest increase in non-VRE capacity within this period was found in Germany (15 GW) and Italy (8 GW). The VRE penetration was negligibly small in this period.

From 1994-2007, the total electricity generation increased by 25% from 1,255 TWh to 1,565 TWh, while the non-VRE capacity increased by 20%, from 277 GW to 331 GW. The largest increases were found in Italy (26 GW), Romania (14 GW) and the UK (13 GW). Non-VRE capacity in Germany within this period decreased with 5 GW, while hydropower (2 GW), PV (4 GW) and wind power (22 GW) increased. These increases in PV and wind capacity in Germany accounted for the largest share of the 33 GW VRE capacity increase within VRE-medium in this period. The slightly higher increase in total electricity generation in this period compared to the non-VRE capacity (25% versus 20%) caused an 8% increase in full load hours from 4,546 to 4,911.

Between 2007-2010, the implementation of VRE started increasing, as the installed VRE capacity rose from 33 GW to 63 GW, a 91% increase. Within this same period, the non-VRE capacity increased from 331 GW to 354 GW, a 7% increase, while the total electricity generation decreased by 2% from 1,565 TWh to 1,530 TWh. A decreasing total electricity generation and an increasing non-VRE and VRE capacity resulted in a decrease in fossil-full load hours. The fossil full load hours decreased by 15% from 4,911 in 2007 to 4,156 in 2010. Even though the absolute increase in VRE capacity is higher than the absolute increase in non-VRE capacity, 30 GW versus 23 GW, the decrease in fossil full load hours is most likely allocated for the greater part to the increase in non-VRE capacity. This is due to the lower capacity factors of VRE installations compared to fossil-fired power plants, as explained in paragraph 4.3.1.

In the most recent period, between 2010-2014, the total electricity generation decreased by 6% from 1,530 TWh to 1,435 TWh, while the non-VRE capacity decreased as well, by 3% from 354 GW to 344 GW, mostly caused by the (partially) decommissioning of coal-fired power plants in the UK. These developments have a neutralizing effect, which would results in a small decrease in full load hours of at least lower than 6% (i.e. the effect of decreasing total electricity generation on full load hours in the installed capacity would remain constant). Within this period, the VRE capacity increased by 117% from 63 GW to 137 GW, equal to an increase in VRE penetration from 5% to 13%. Therefore, since the effect of total electricity generation and non-VRE capacity was minimal within this period, the 21% decrease in fossil full load hours from 4,156 to 3,264 is for the greater part allocated to the increase in VRE penetration.

While the total fossil full load hours remained fairly constant between 1990-1999, the full load hours of the individual fuels experienced larger fluctuations. A shift from coal to gas is visible between 1990-1999 when coal full load hours decreased from 6,005 to 4,458 and gas full load hours increased from 3,839 to 5,533. This was mainly caused by gas-fired capacity being used as peaking units in beginning years of the timeframe. Gas-fired capacity was only 24 GW in 1990, compared to 104 GW of coal capacity. In 1999, the gas capacity was expanded to 56 GW mainly by the commissioning of base load CCGTs, while production from gas-fired power plants increased from 132 TWh in 1990 to 333 TWh in 1999. Coal-fired capacity increased only by 4% within this period, while electricity generated from coal decreased by 23% from 608 TWh to 468 TWh. The decrease in fossil full load hours from 2007-2014 is mainly allocated to a decrease in gas-fired full load hours, which decreased by 53% from 4,921 to 2,329. Coal full load hours have only decreased by 12% from 5,590 to 4,925 within the same period. The oil-fired full load hours decreased from 1995-2014 for almost every year, resulting in 1,175 full load hours in 2014.

In Figure 20, the trends of import + export and VRE penetration are plotted. The share of import + export seems to rise at a similar rate compared to the VRE penetration. This is confirmed by the correlation graph of Figure 52, in Appendix D. The correlation factor was found to be very strong with 0.87. The same note is made as with the high VRE group, import + export grows within this timeframe also because the cross-border connections are expanded and non-renewable electricity is exchanged as well for financial motives.

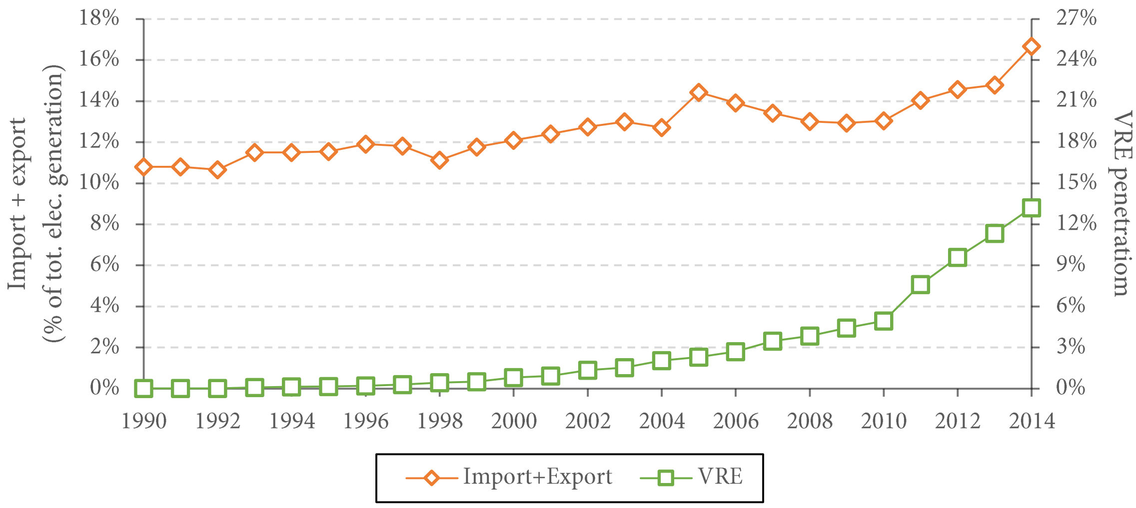

Figure 20: VRE and import + export trends in VRE-medium.

4.4.2 Efficiency

In Figure 21, the trends in energy efficiency and average year of commission of coal-fired power plants in VRE-medium are presented. Coal efficiency was 35% at the start of the trend, in 1990. The coal efficiency then increased until a peak was reached in 2003, at 39% efficiency. This efficiency increase was caused by the construction of new coal-fired power plants, indicated by the increase in average year of commission from 1972 to 1977. Most of this newly installed coal capacity is allocated to Germany and Italy, where 2 GW and 3 GW of new coal capacity was installed within this period, respectively. From 2003 onwards, the efficiency levelled between 38% and 39%, which is explained by the levelling average year of commission, which only increased by 2 years from 1977 to 1979 between 2003-2011. Small fluctuations within this last period are most likely the cause of either uncertainties in statistics, power plant specific factors mentioned in the theoretical framework (i.e. retrofitting, fuel quality, quality of maintenance and biomass co-firing), or the effect of VRE intermittency. The very strong dependency of coal efficiency on the average year of commission is confirmed by Figure 22 which generates a correlation coefficient of 0.93.

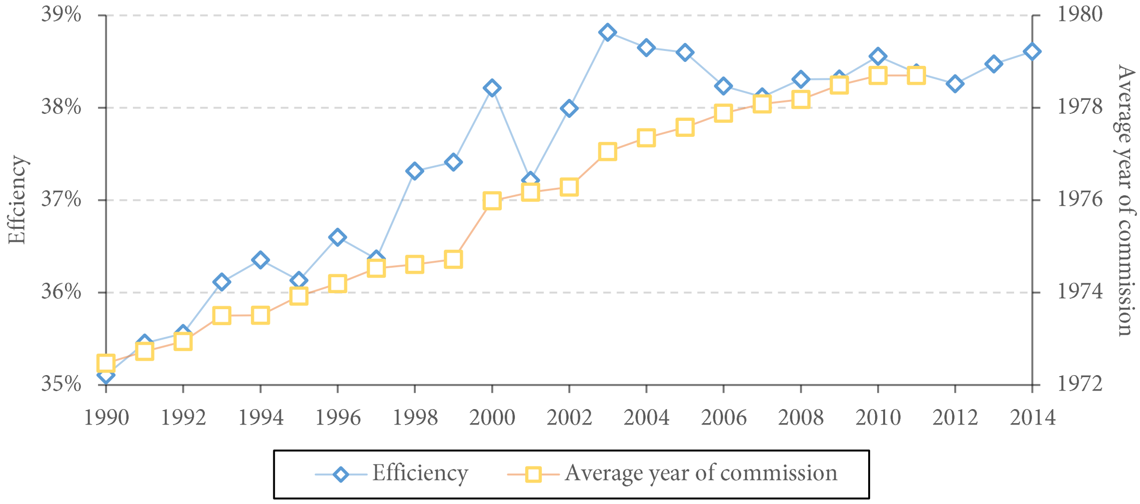

Figure 21: Efficiency and average year of commission trends of coal-fired power plants in VRE-medium.

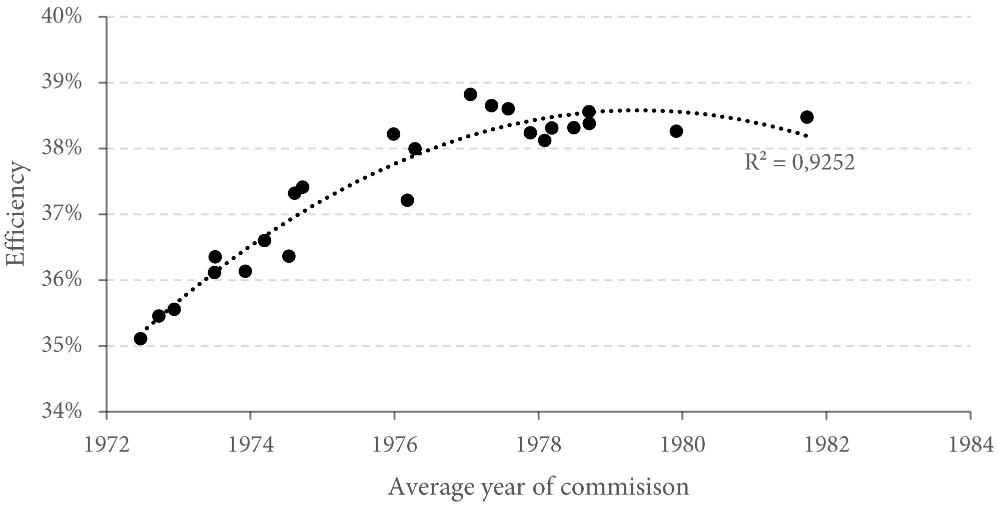

Figure 22: Correlation average year of commission and efficiency of coal-fired power plants in VRE-medium.

In Figure 23, the trends in efficiency and average year of commission of gas-fired power plants are presented for VRE-medium. Similar to coal-fired power plants in this VRE penetration group, the correlation was found to be very strong between these two trends: 0.90, as indicated in Figure 24. The efficiency of gas-fired power plants experienced a large increase from 1992 to 2008, where efficiency increased from 38% to 50%. Within this period the average year of commission increased rapidly from 1975 to 1997, caused by the construction of new gas-fired power plants. The largest increase in capacity was found in Italy (32 GW) and the United Kingdom (30 GW). From 2008-2014 the efficiency levelled between 49% and 50%. This is explained for a large part by the decreasing growth in average year of commission in the latest available years, from 2007-2011. The increase in average year of commission is 0.6 per year between 2007-2011, while over the period 1990-2007 the increase was 1.4 per year. For the last years within the timeframe for which no average year of commission data was available, 2012-2014, the efficiency would level if no new gas-fired capacity would be installed. The efficiency levels within this period, so either no new capacity was installed, or there was new capacity installed and other factors, which have been mentioned in the previous paragraph, have caused the efficiency to level.

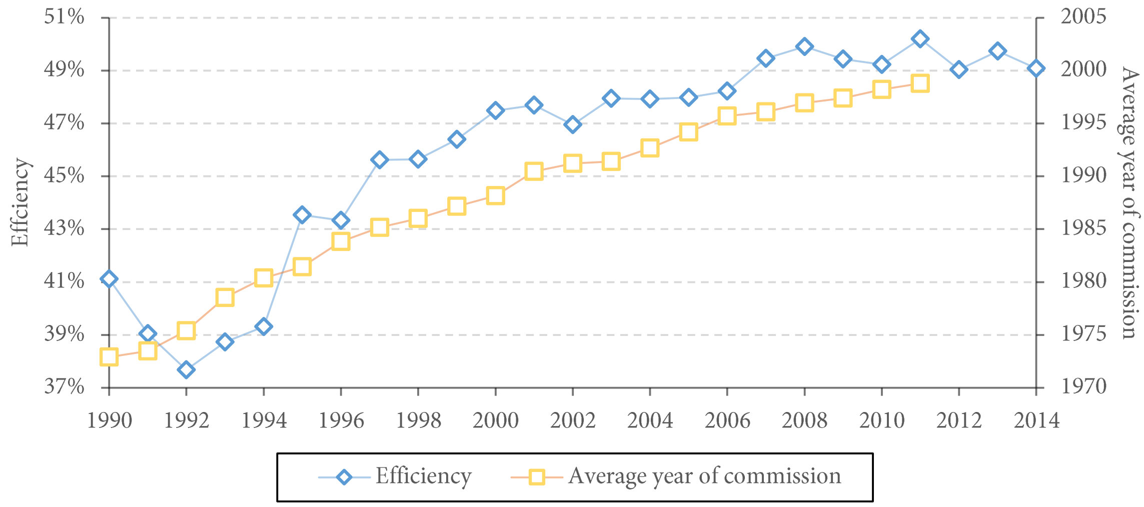

Figure 23: Efficiency and average year of commission trends of gas-fired power plants in VRE-medium.

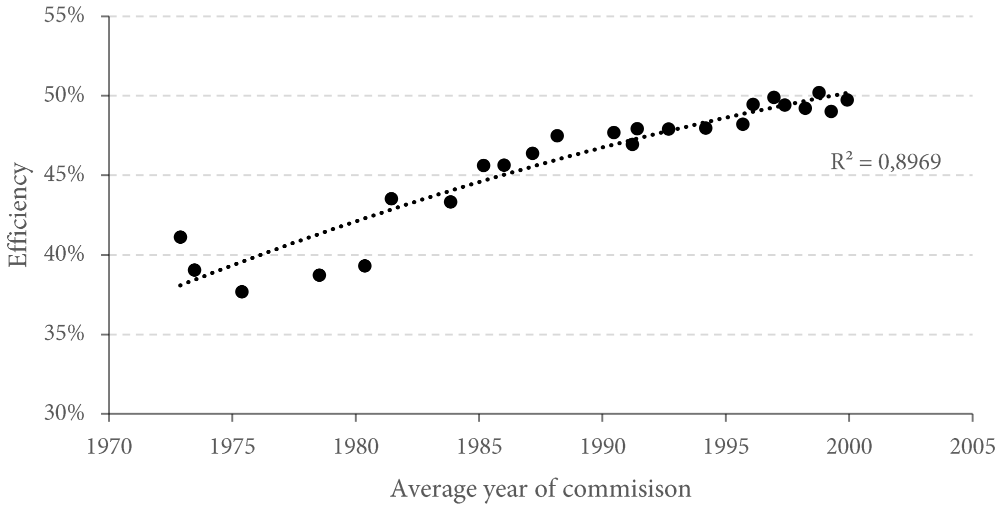

Figure 24: Correlation average year of commission and efficiency of gas-fired power plants in VRE-medium.

Conclusion

Between 2010-2014, the decrease in fossil full load hours was found to be for the greater part caused by an increasing VRE penetration. The total electricity generation decreased by 6% while the non-VRE capacity decreased as well, by 3%. Due to the neutralizing effect these two development have on each other, the 21% decrease in fossil full load hours, from 4,156 to 3,264, is most likely for the greater part caused by an increase in VRE penetration from 5% to 13%.

The energy efficiency of both coal- and gas-fired power plants were found to be very strongly dependent of the average year of commission. Coal efficiency levelled between 38% and 39% from 2003-2014 and gas efficiency levelled between 49% and 50% between 2008-2014. Both of these levelling trends were explained for a large part by a decrease in the growth of average year of commission, indicating less new capacity was installed. The levelling of the efficiencies even though still some new capacity was installed may be explained by several factors: uncertainty in statistics, power plants specific factors (i.e. retrofitting, fuel quality, quality of maintenance and biomass co-firing) or VRE intermittency.

4.5 VRE-low

The VRE-high group consists of Austria, Bulgaria, Cyprus, Estonia, Finland, France, Hungary, Malta, Netherlands, Poland, Slovakia, Slovenia and Sweden. Averaged over the timeframe 1990-2014, the country's individual shares of the total fossil electricity generation are 1% for Malta, Cyprus, Slovakia and Sweden, 2% for Sweden, 3% for Estonia, 4% for Austria, 5% for Hungary, 6% for Bulgaria, 7% for Finland, 12% for France, 21% for Netherlands and 36% for Poland.

4.5.1 Full load hours

Similarly to the other two VRE penetration groups, the total electricity generation increased within the first period of the timeframe, from 990 TWh in 1990 to 1,252 TWh in 2008, as can be seen in Figure 25. In comparison with VRE-high and VRE-medium, the decrease in total electricity generation after 2009 is smaller. More than that, in 2010 the highest total electricity generation was reached within the timeframe 1990-2014: 1,273 TWh. From 2010-2014, the total electricity generation decreased by 3%. The variation in electricity generation from the individual fuels is minimal within the timeframe. Noticeable differences are identified in gas-fired power plants, which experienced a gradual increase from 1990-2010, where a peak of 152 TWh is reached. From 2010-2014 electricity produced from gas-fired power plants decreased from 152 TWh to 97 TWh. Nuclear is the highest source of electricity generation within this VRE penetration group, caused by the dominance of nuclear power in France. France accounted for almost 80% of all nuclear electricity generation within the VRE-low. Oil electricity generation was fairly constant within the whole timeframe, while other renewables increased by 65 TWh from 204 TWh in 2003 to 269 TWh in 2014. Coal reached small, local peaks in 2003, 2006 and 2007 and started decreasing after 2007. As can identified from the figure, VRE generation was small in this aggregated country group, only 60 TWh in 2014.

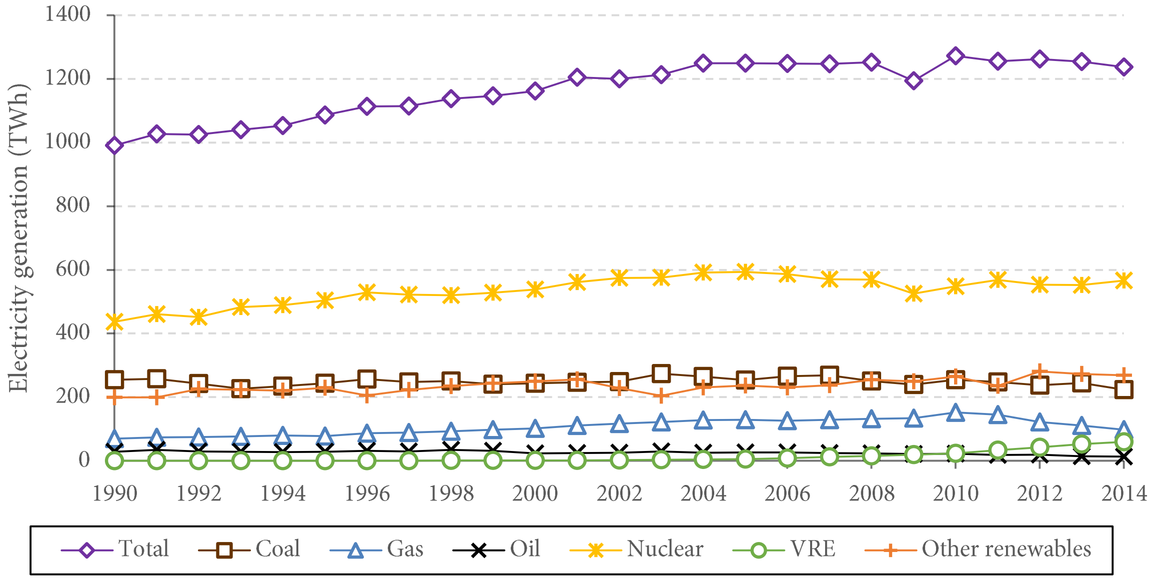

Figure 25: Electricity generation trends by source in VRE-low.

In Figure 26 the trends in non-VRE capacity, VRE capacity and total electricity generation are plotted. In Figure 27 the trend in full load hours are plotted.

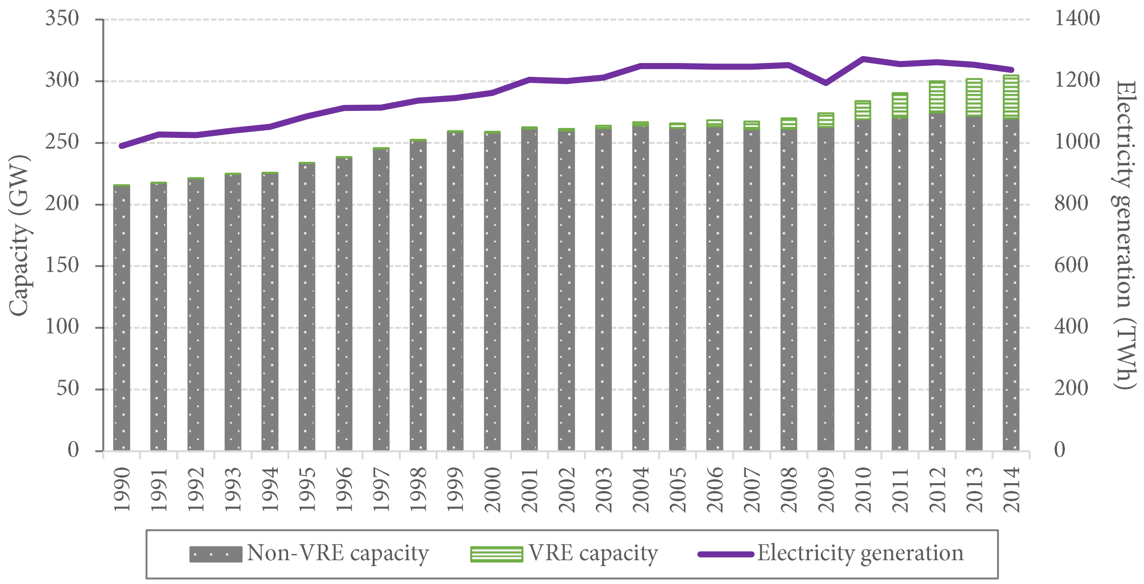

Figure 26: Non-VRE capacity, VRE capacity and total electricity generation trends in VRE-low.

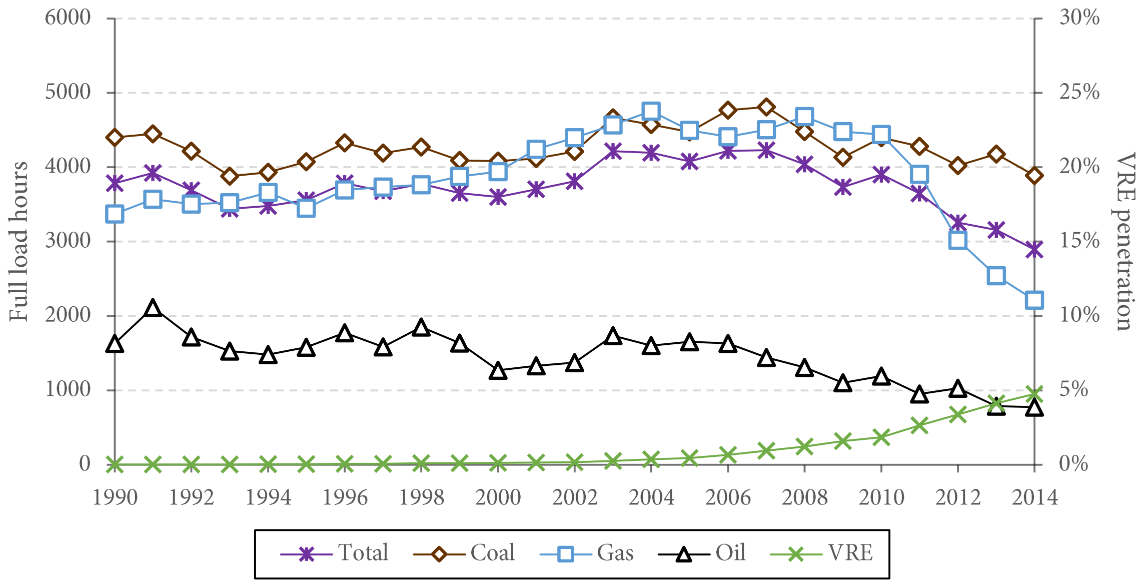

Figure 27: VRE and full load hour trends in VRE-low.

Since VRE penetration was relatively low in this group, especially in the first three-quarter part of this timeframe, the fluctuations in fossil full load hours were caused by developments in total electricity generation and installed non-VRE capacity. In 2009, the total electricity generation decreased by 5% while the non-VRE capacity increased with 1%, leading to the largest decrease in fossil full load hours within the timeframe. From 2010-2014, the full load hours decreased from 3,904 to 2,895, a decrease of 26%. In this period, the VRE capacity increased by 133% from 15 GW to 35 GW. Even though the percentage increase of 133% appears to be a large increase, the VRE penetration was only increased from 2% to 5%. Therefore, the decrease in full load hours within this period was most likely caused by developments in total electricity generation and non-VRE capacity. The total electricity generation decreased from 1,273 TWh to 1,237 TWh (-3%) and the non-VRE capacity increased from 268 GW to 270 GW (+1%) within this same period.

When breaking down the fossil full load hours into individual full load hours, it can be identified that the full load hours of coal and gas run parallel to the total fossil full load hours from 1990-2010. The decrease in fossil full load hours from 2010-2014 is mainly allocated to gas-fired power plants, as the average full load hours for these power plants decreased from 4,440 to 2,215, likely caused by the relatively higher natural gas price compared to coal as mentioned earlier in the VRE-high and VRE-medium section of the results.

The trends of import + export and VRE penetration of VRE-low are presented in Figure 28. The correlation between these two trends was found to be very strong, with a correlation coefficient of 0.81, calculated by Figure 53 in Appendix D. The same note is made as in the previous VRE penetration groups that both trends increase over time independent of each other and therefore the correlation is biased. The percentage of import + export of total electricity generation was higher in VRE-low compared to the other VRE penetration groups: VRE-low between 13%-28%, as shown in Figure 28, compared to varying penetration levels in VRE-high of 8%-18% and VRE-medium 11%-17%. The high import + export was mainly caused by Austria, The Netherlands, Slovakia and Slovenia who had shares of import + export compared to their national total electricity generation of 67%, 49%, 91% and 99% in 2014, respectively. These results indicate that a different factor was of higher influence on the amount of import + export than VRE penetration, most likely financial motives. This implicates that countries will more likely be trading (non-VRE) electricity based on electricity prices in neighbouring countries than (VRE) electricity surplus or shortage due to VRE intermittency.

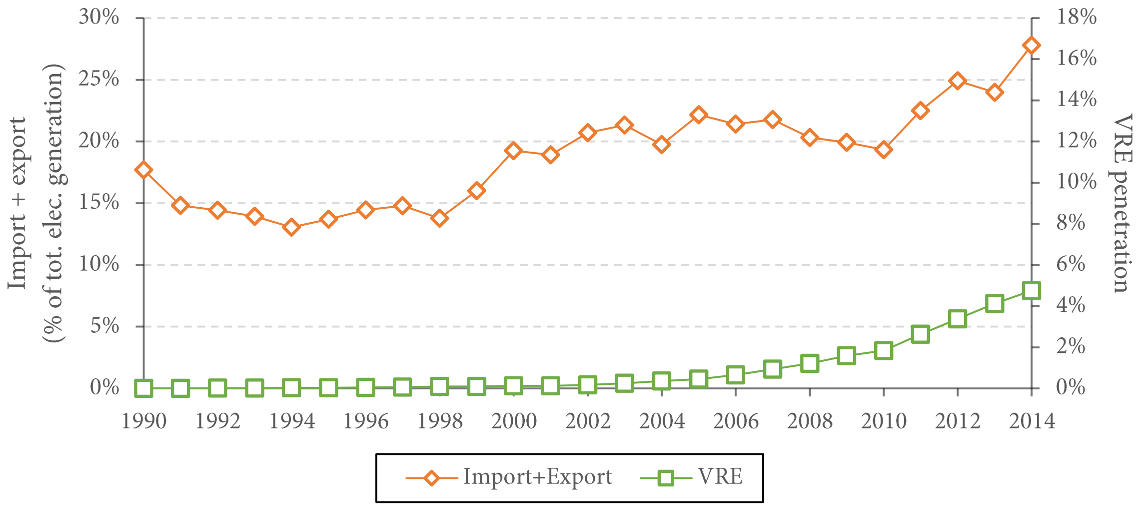

Figure 28: VRE and import + export trends in VRE-low.

4.5.2 Efficiency

In Figure 29, the trends in efficiency and average year of commission of coal-fired power plants in VRE-low are presented. In Figure 30, the correlation between these two trends is plotted, resulting in a very strong correlation of 0.93. The coal efficiency increased from 34% in 1990 to 37% in 2003. From 2003-2014 the efficiency levelled between 36% and 37% even though the average year of commission was still increasing, indicating installation of new coal-fired power plants. This development was mainly caused by Poland, as Polish coal-fired electricity generation was 54% of the total coal-fired electricity generation in 2003 in VRE-high. A possible cause for the levelling efficiency in new Polish coal-fired power plants is a factor from the theoretical framework, namely fuel quality. The newly constructed coal-fired power plants in Poland within this period were lignite-fuelled. Lignite has one of the lowest energy densities of all types of coal and lignite-fuelled power plants have lower efficiencies compared to power plants fuelled by higher quality coal types (Radgen, 2006).

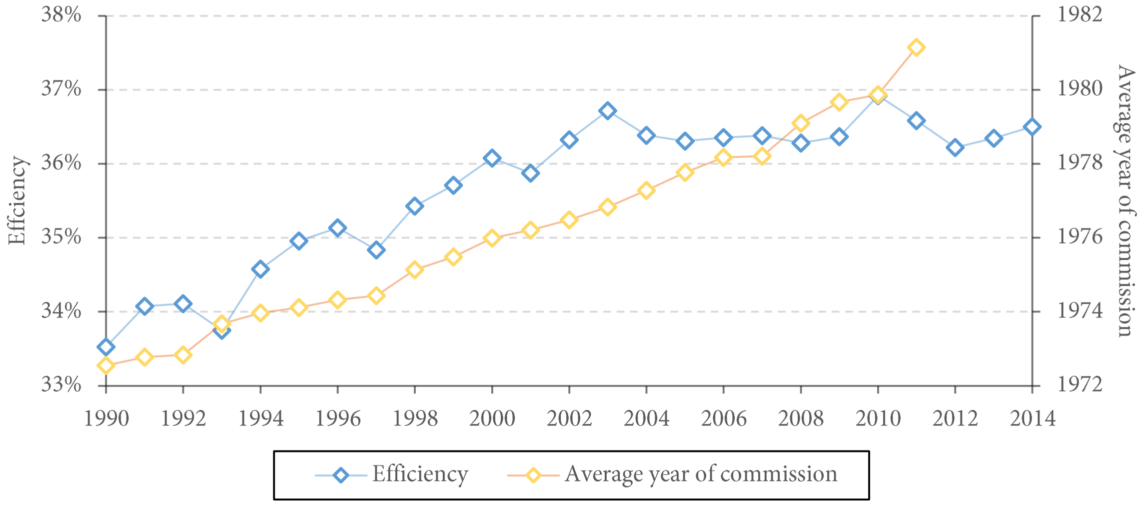

Figure 29: Efficiency and average year of commission trends of coal-fired power plants in VRE-low.

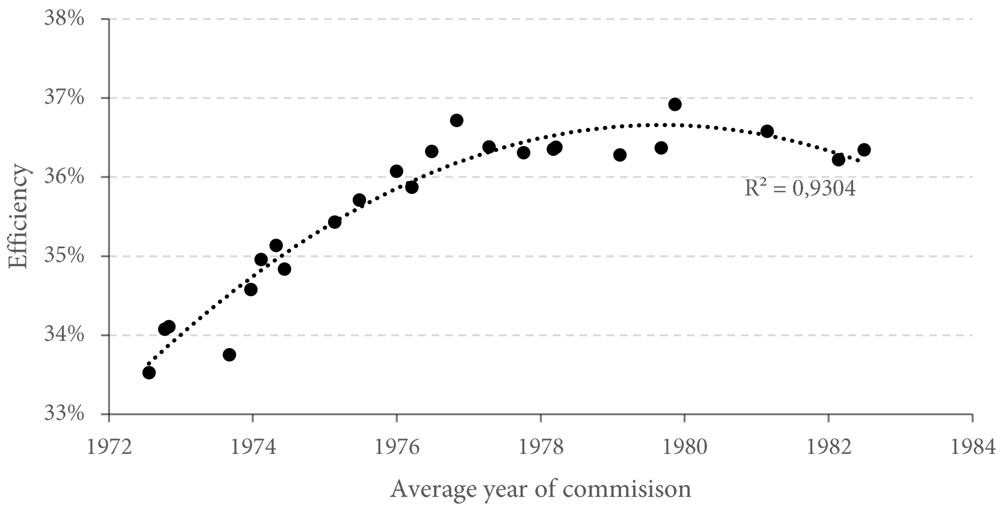

Figure 30: Correlation average year of commission and efficiency of coal-fired power plants in VRE-low.

In Figure 31, the trends in efficiency and average year of commission for gas-fired power plants in VRE-low are presented. The correlation between these two trends was found to be very strong, similar to coal, with a correlation coefficient of 0.81, as presented in Figure 32.

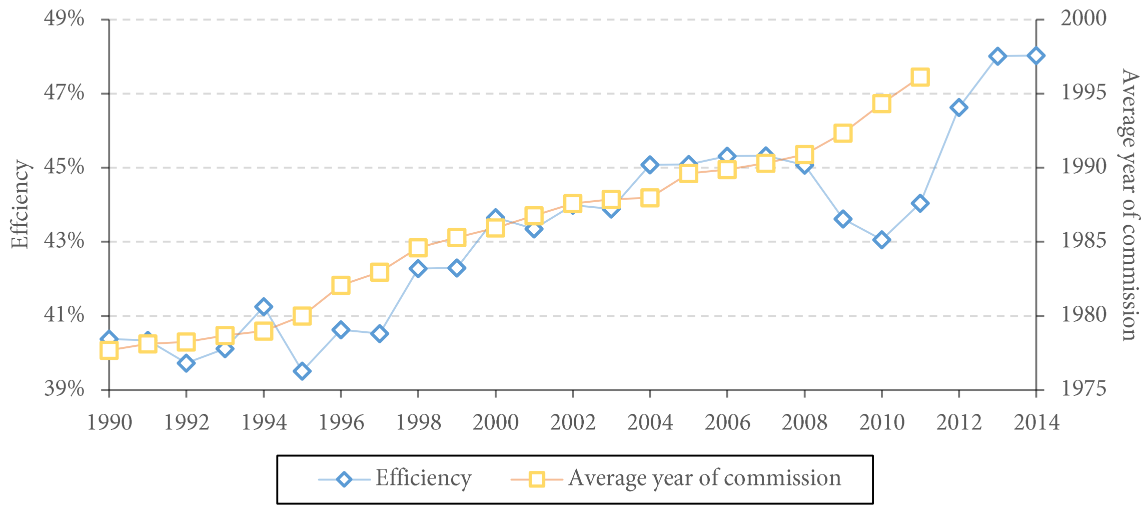

Figure 31: Efficiency and average year of commission trends of gas-fired power plants in VRE-low.

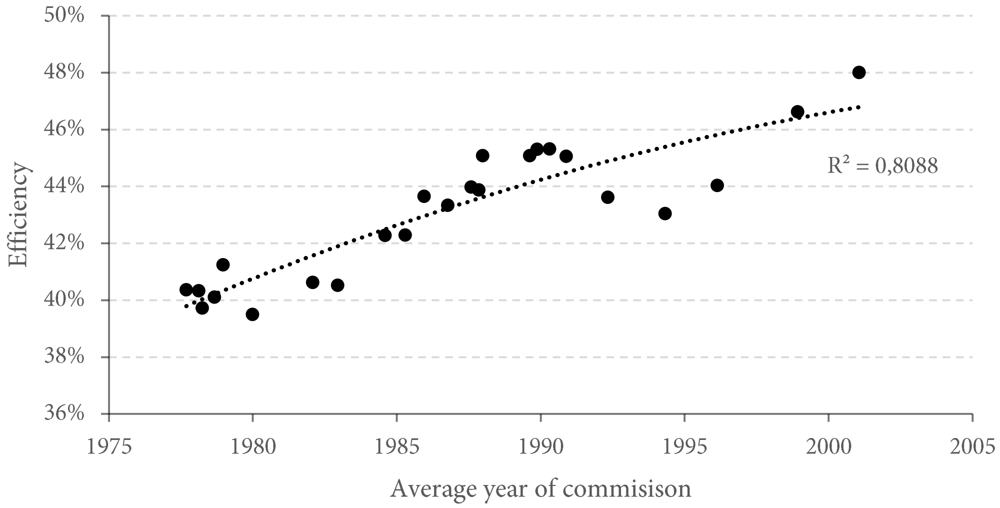

Figure 32: Efficiency and average year of commission trends of gas-fired power plants in VRE-low.

Gas efficiency gradually increased from 40% in 1990 to 45% in 2008. Within this period the average year of commission increased from 1978 to 1991. The gas efficiency then reached a local minimum in the years 2009-2011, even though the average year of commission increased within this period. This efficiency decrease was caused by France, which, in 2009, consisted of 19% of the total gas-fired electricity generation in VRE-low. The development of gas-fired efficiency in France for the most recent 10 years is presented in Figure 33 below.

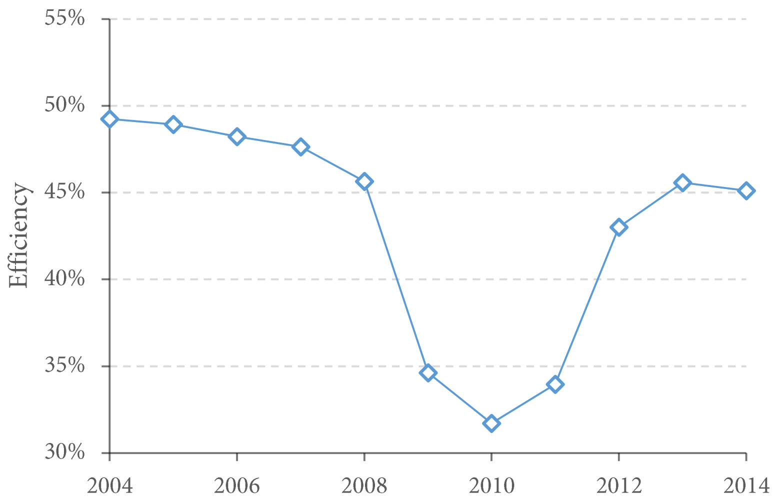

Figure 33: Gas-fired efficiency trend of France between 2004-2014.

The gas efficiency in France decreased from 46% in 2008 to 35% in 2009. After efficiencies of 32% and 34% in 2010 and 2011, respectively, the efficiency increases again in 2012 to 43%. These large fluctuations may be caused by the gas-fired power plants in France only being used as peaking units. The electricity landscape in France is dominated by nuclear power. In 2009, nuclear electricity generation consisted of 76% of the total generation, while gas-fired electricity generation consisted of 4% of total electricity generation. The relatively small amount of gas-fired power plants in France, consisting of mainly SCGTs, being used as peaking units explains the large fluctuations in VRE-low (Hussy et al., 2014).

Conclusion

The only period in which full load hours were found to be decreasing was between 2010-2014, where the full load hours decreased by 26% from 3,904 to 2,895. Since the total electricity generation decreased by 3% within this period, from 1,273 TWh to 1,237 TWh, and the non-VRE capacity increased by 1% from 268 GW to 270 GW, the decrease in full load hours is most likely the result of the development of these two trends and not the result of an increase in VRE penetration. VRE capacity did increase by 133%, but only from 15 GW to 35 GW, representing an increase in VRE penetration of only 2% to 5%.

The efficiency of coal- and gas-fired power plants was found to be very strongly dependent on the average year of commission. Coal efficiency increased from 34% in 1990 to 37% in 2003. Even though the average year of commission continued to increase, the efficiency levelled after 2003. This was found to be possible caused by the construction of low efficiency lignite plants in Poland, responsible for 54% of the total electricity produced from coal in VRE-low. Gas efficiency increased steadily from 40% in 1990 to 48% in 2014, with the exception of three years between 2009-2011. This was caused by the lower efficiency in these years in France, where gas-fired capacity is dominated by SCGTs used as peaking units.

4.6 Comparison of VRE-high, -medium and -low

4.6.1 Full load hours

In Figure 34, the trends of total electricity generation and VRE penetration of the three VRE penetration groups are presented. All three trends show increasing levels of total electricity generation from 1990-2008. In 2009, as a an effect of the financial crisis, total electricity generation decreased, which is visible in all three trends. The total electricity generation increased again in 2010, after which the trends decreased from 2011-2014. The relative decrease in total electricity generation between 2011-2014 was 8%, 6% and 3% for VRE-high, VRE-medium and VRE-low, respectively. The VRE penetration in VRE-high was increasing since the beginning of the timeframe in 1990, until 25% in 2014. The growth of VRE in VRE-medium and VRE-low started slowly but both trends show increased growth from 2011-2014, where VRE-medium increases from 5%-13% and VRE-low from 2%-5%.

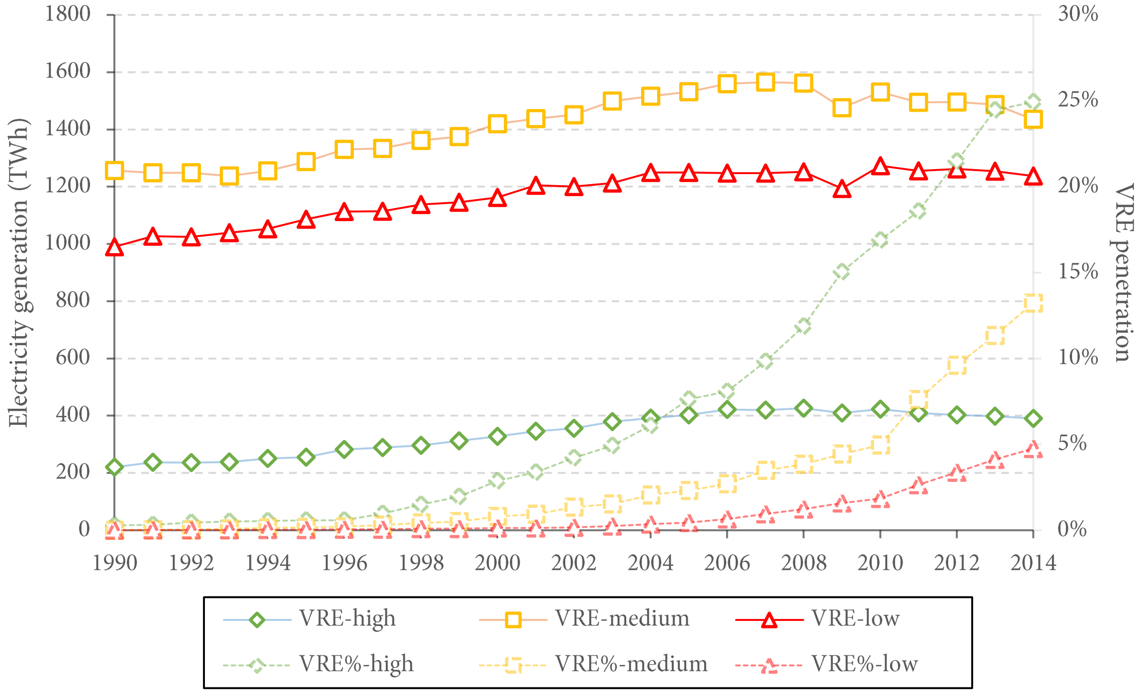

Figure 34: Total electricity generation and VRE trends of the VRE penetration groups.

The trends in non-VRE capacity are presented in Figure 35 below. The fluctuations in installed non-VRE capacity vary per VRE penetration group but in general there was an increasing overall trend found for the first 20 years of the timeframe. In VRE-high, the non-VRE capacity increased, aside from 2004, until 2010, after which the capacity decreased by 3% from 2010-2014. The non-VRE capacity in VRE-medium increased, aside from 2003, until 2011, after which the capacity decreased by 4% from 2011-2014. The non-VRE capacity of VRE-low experienced multiple single year decreases in non-VRE capacity within the first years of the timeframe. A longer trend consisting of multiple decreasing data points is only found in the latest two years, 2012-2014, when the installed non-VRE capacity decreased by 1%.

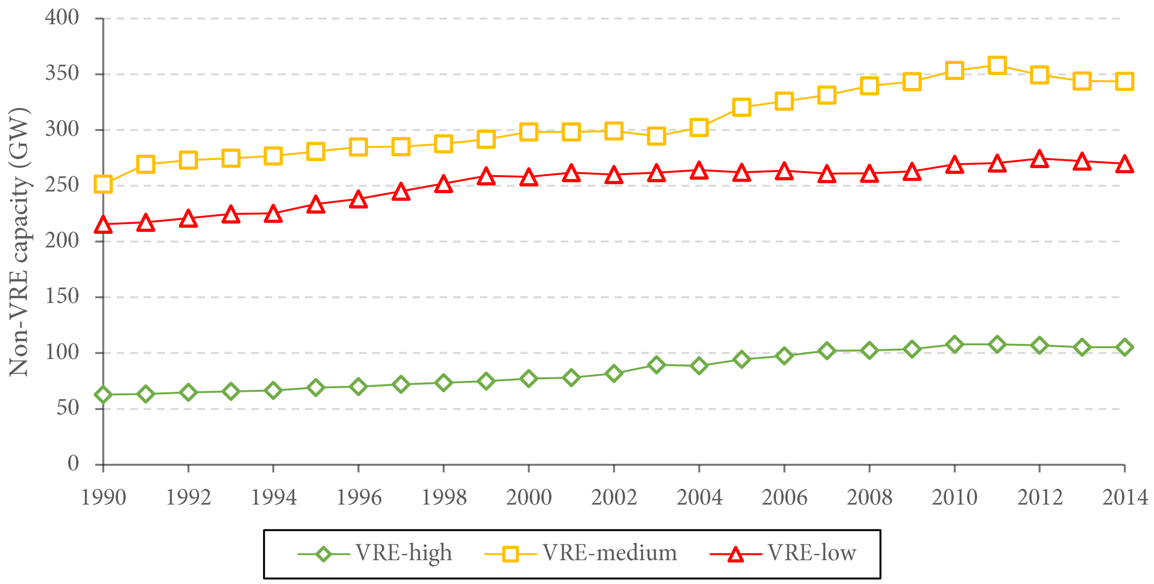

Figure 35: Non-VRE capacity trends of the VRE penetration groups.

In Figure 36, the fossil-fired full load hours trend of VRE-high, -medium and -low are presented. Between 1990-2005 the fossil full load hours of the VRE penetration groups remained fairly constant, and fluctuations were relatively small. Full load hours of VRE-high and VRE-medium varied around 4,500 and VRE-low full load hours varied around 4,000. From 2005-2014 the full load hours of VRE-high started decreasing from 4,936 to 2,344, a decrease of 53%. The full load hours of VRE-medium started decreasing from 2007-2014, from 4,911 to 3,264, a decrease of 34%. The full load hours of VRE-low started decreasing at the latest point, from 3,904 in 2010 to 2,895 in 2014, a decrease of 26%.

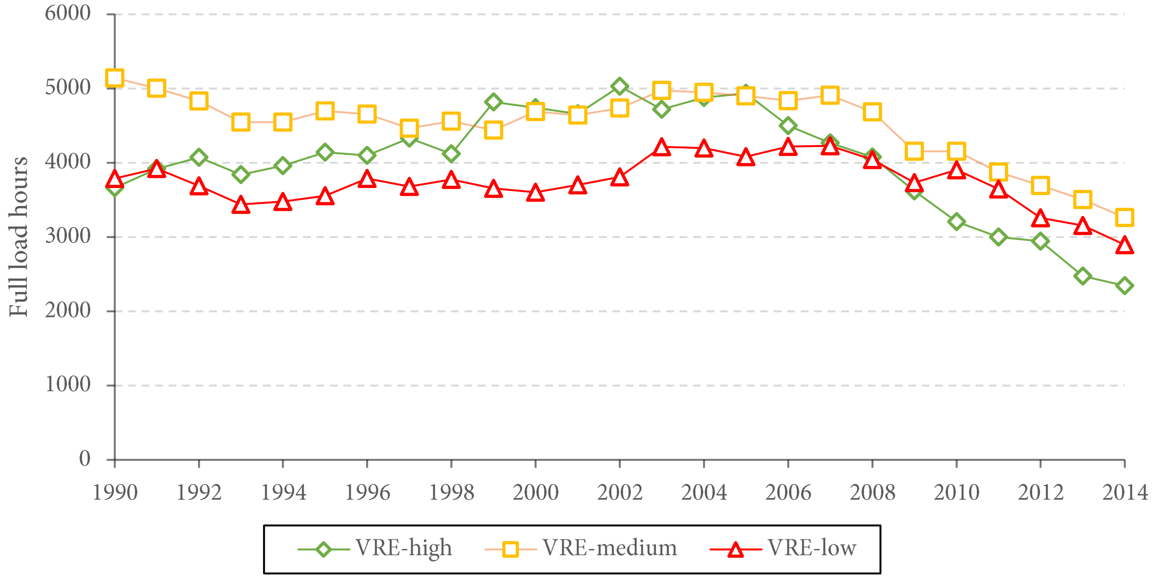

Figure 36: Fossil-fired full load hour trends of the VRE penetration groups.

The fossil full load hours are determined by the three factors of total electricity generation, VRE penetration and non-VRE capacity. The abovementioned fossil full load hour decreases within the VRE penetration groups can therefore not be solely allocated to an increase in VRE penetration. During the largest part of these periods of decreasing full load hours, the total electricity demand and non-VRE capacity were increasing, while the growth of VRE penetration was low. Only in most recent years, between 2010-2014, in VRE-high and VRE-medium the decreasing full load hours were found to be caused for the greater part by an increased VRE penetration from 17% to 25% and from 5% to 13%, as the trends in total electricity generation and non-VRE capacity had a partly neutralizing effect on each other. The decreasing full load hours in VRE-low between 2010-2014 was found to be caused for the greater part by a decreasing total electricity generation (3%) and an increasing non-VRE capacity (1%). The VRE penetration was still relatively small within this period, increasing from 2% to 5%.

In Figure 37 the import + export trends of the three penetration groups are presented. The correlations between import + export in all VRE penetration groups were found to be very strong. However, these correlations are biased as both increase over time, independently of each other. The figure shows that the relative import + export of the total electricity generation is highest in VRE-low. This indicates that a different, more dominant factor is affecting the share of import + export. This is most likely due to financial motives, as countries may prefer to import electricity of a lower price from a neighbouring country instead of producing the electricity themselves at a higher price, or having to build new capacity.

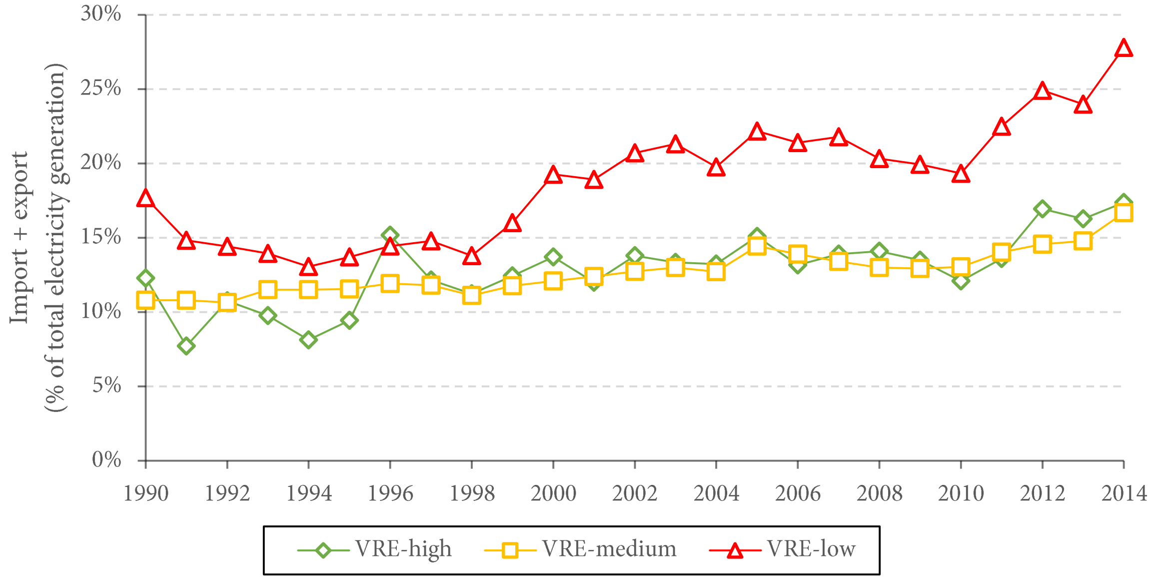

Figure 37: Import + export trends of the VRE penetration groups.

Conclusion

The trends in total electricity generation and non-VRE capacity increased from 1990-2008 for all VRE penetration groups. While decreasing between 2008-2014 in VRE-high and VRE-medium, the two trends more or less levelled in VRE-low. The fossil full load hours decreased in VRE-high by 53% from 2006-2014, in VRE-medium by 34% from 2007-2014 and in VRE-low by 26% from 2010-2014. However, due to the trends in total electricity generation and non-VRE capacity, only the full load hours decreases from 2010-2014 in VRE-high and VRE-medium can be allocated for the greater part to increasing VRE penetration. Import + export was found to be highest in VRE-low, indicating that a more dominant factor is of influence on import + export besides VRE penetration.

4.6.2 Efficiency

In Figure 38, the coal efficiency trends of the VRE penetration groups are presented and in Figure 39 the trends in average year of commission. The correlations between the two trends were found to be very strong for VRE-medium and VRE-low but very weak for VRE-high. This was caused by the small amount of newly installed capacity which increased the sensitivity of small efficiency fluctuations, caused by either uncertainties in statistics or intermittency of VRE. The higher coal efficiency of VRE-high, fluctuating around 39%, compared to the other VRE penetration groups was caused by the higher average year of commission. The coal efficiencies of VRE-medium and VRE-low run parallel to each other but the efficiency in VRE-medium is between 1.5% and 2% higher during the whole timeframe, while the trends in average year of commission are almost identical. This is explained by the dominance of lower efficiency lignite-fuelled power plants in VRE-low countries like Bulgaria, Hungary, Slovakia and partly Poland, compared to VRE-medium countries where no lignite-fuelled plants are installed in Italy and the UK, and only partly in Germany. The coal-fired power plants in these countries were mostly fuelled by bituminous coal, which yields a higher energy efficiency due to its higher energy density.

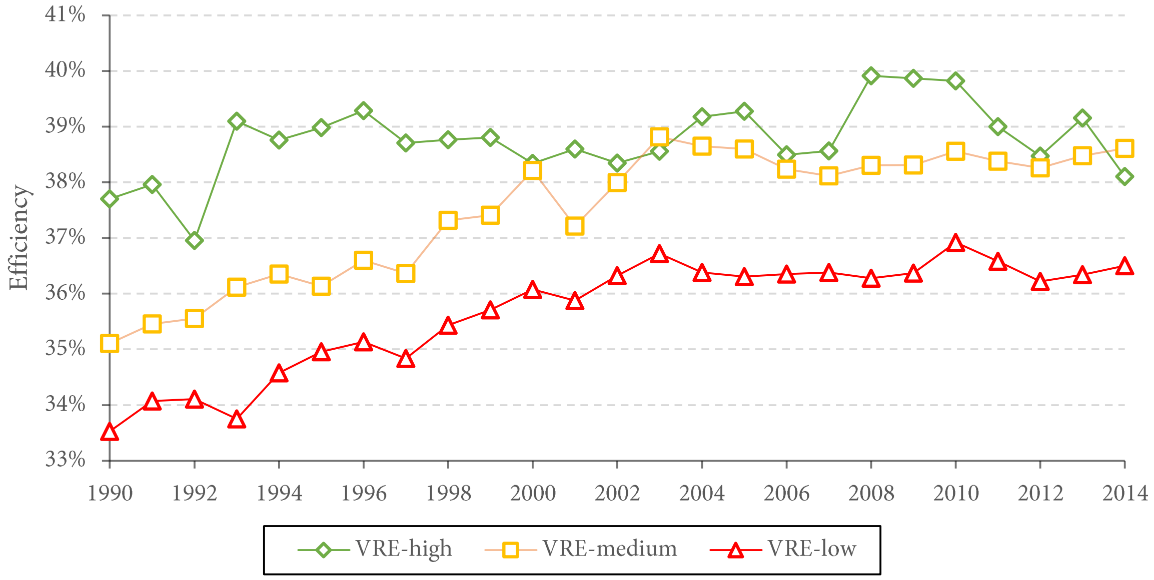

Figure 38: Coal efficiency trend of the VRE penetration groups.

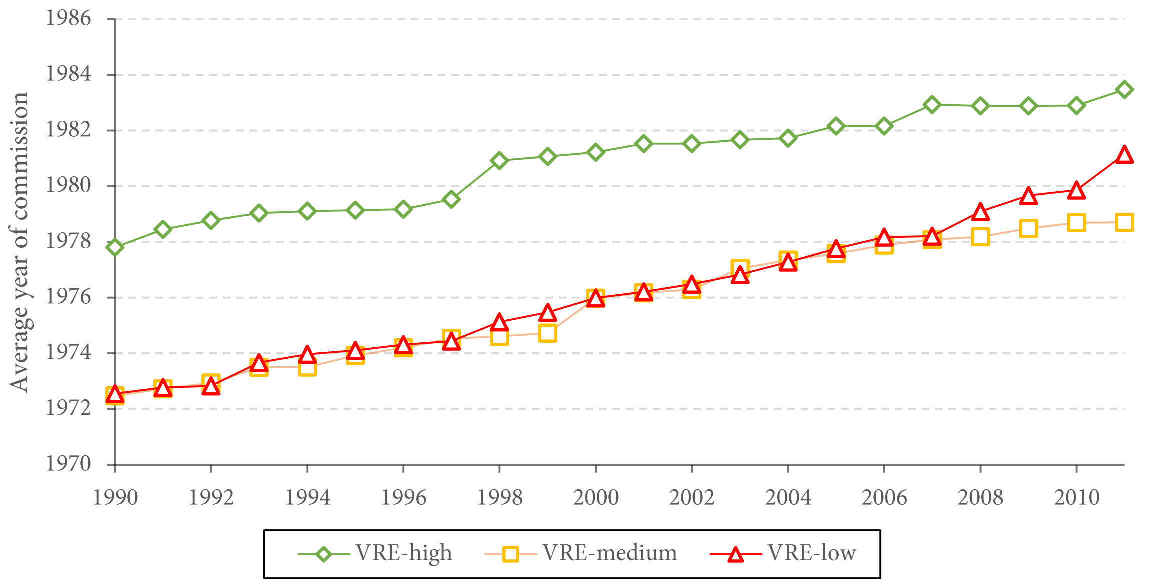

Figure 39: Average year of commission trends of coal-fired capacity in the VRE penetration groups.

The trends of gas efficiency are presented in Figure 40 and the trends in average year of commission in Figure 41. A very strong correlation was found between the average year of commission of gas-fired power plants and efficiency in all three VRE penetration groups. In all three VRE penetration groups the efficiency increased at similar rates between 1990-2003, while also the average years of commission increased at similar rates. A different trend is identified from 2002 onwards in VRE-high, as the efficiency increased at a much higher rate compared to the other VRE penetration groups. This was caused by the rapid installation of new CCGTs in Spain, leading to a large increase in average year of commission. In VRE-high, a decrease in efficiency was identified for the years 2009-2011, caused by the low efficiency of gas-fired power plants in France, which are used mainly as peaking units. In the most recent four years, from 2011-2014, the gas efficiency decreases in VRE-high which is most likely caused by VRE intermittency, causing more start-ups and stops and part load operation which negatively affects the efficiency.

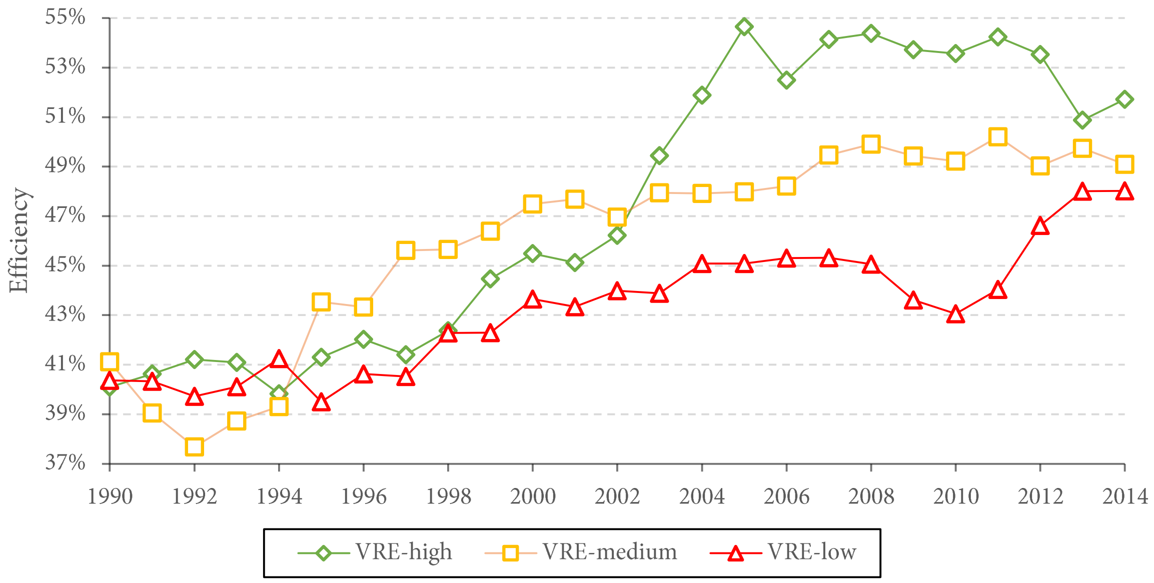

Figure 40: Gas efficiency trends of the VRE penetration groups.

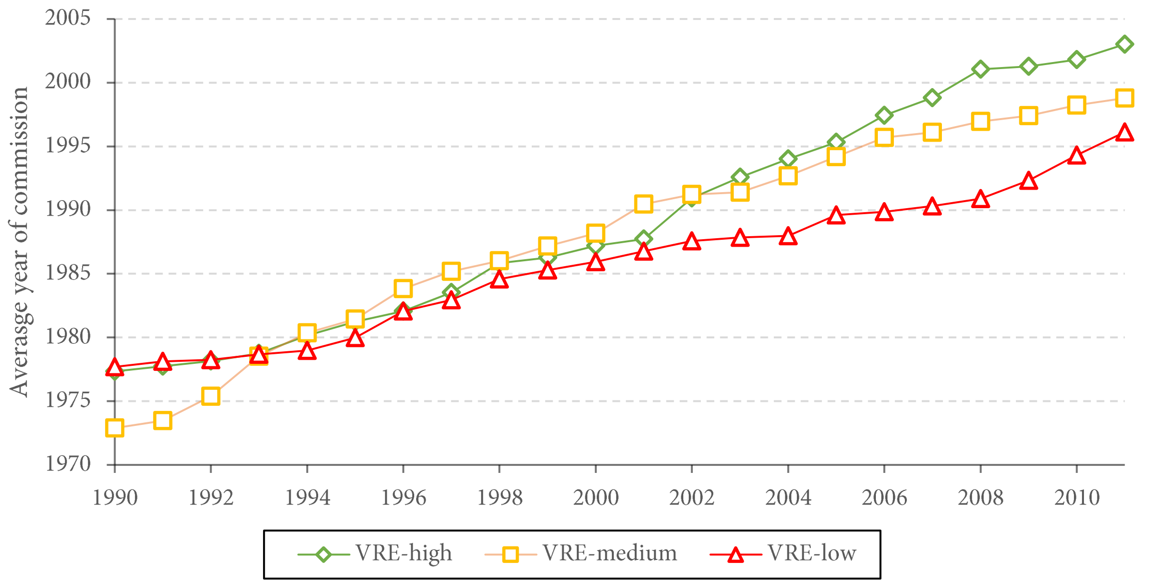

Figure 41: Average year of commission trends of gas-fired power plants in the VRE penetration groups.

Conclusion

Coal and gas efficiency were both found to be very strongly dependent of the average year of commission. The coal efficiency was highest in VRE-high, due to the higher average year of commission. In the latest four years, a clear decrease is visible in coal efficiency within this VRE penetration group, most likely the effect of VRE intermittency. While the trends in average year of commission in VRE-medium and VRE-low are almost equal, the efficiency in VRE-low was lower due to the high share of lignite-fuelled power plants compared to the dominancy of the higher efficient bituminous coal in VRE-medium. Gas efficiency was highest in VRE-high, where the installed capacity was most modern. The gas efficiency decrease from 54% to 52% in the most recent four years is most likely the effect of VRE intermittency.

4.7 Comparison of results with literature results

In this section, the results regarding the effect of VRE on full load hours and energy efficiency from this research are compared with the results found in literature.

4.7.1 Full load hours

Decreases allocated for the greater part to an increase in VRE penetration were found in VRE-high and VRE-medium. In VRE-high the fossil full load hours decreased by 861 full load hours (27%) from 3,205 in 2010 to 2,344 in 2014. In VRE-medium the fossil full load hours decreased by 892 full load hours (21%) from 4,156 in 2010 to 3,264 in 2014. The VRE penetration within these VRE penetration groups increased from 17% to 25% and from 5% to 13%. In literature, there are two studies which experience similar increases in VRE penetration: The NYISO study (NYISO, 2010) where VRE penetration increased from 4% to 13% and the 7.55 GW study (Troy, 2011) which increased from 15% to 29% VRE. Taken into account that the distribution of fossil-fired power production in 2014 is coal 47%, gas 43% and oil 10% in VRE-high, and coal 61%, gas 36% and oil 3% in VRE-medium, the average fossil full load hour decreases according to literature would be 480 in VRE-high and 221 in VRE-low.

So comparing the results from literature with the results of this research, the decreased full load hours in this research are higher than the results from literature. This may be caused by deviating conditions in the literature studies, for example the lacking of PV in the VRE penetration increases or a possible higher decommissioning rate of non-VRE capacity in literature studies compared to the VRE penetration groups.

4.7.2 Efficiency

Efficiency decreases for coal- and gas-fired power plants, caused by increased VRE penetration, were only found in VRE-high. Coal efficiency decreased from 40% to 38% while gas efficiency decreased from 54% to 52%, both within the timeframe 2010-2014 when the VRE penetration increased from 17% to 25%. Efficiency is affected by VRE in two ways: increased start-ups and part load operation. The effect of increased start-ups on coal- and gas-fired power plants was found to be maximum of 0.06pp and 0.5pp, respectively. This would indicate that the largest part of the efficiency decrease found in this research, at least 1.94pp for coal-fired power plants and at least 1.5pp for gas-fired power plants, was caused by part load operation. Even though no direct effect of part load operation due to VRE penetration on power plant efficiency was found in literature, an indication was found of the magnitude of the efficiency fluctuations during part load operation. The average fluctuations for part load efficiency for coal-fired power plants were 38% efficiency at 40% load and 43% efficiency at full load, while the average part load efficiencies of gas-fired power plants varied between 45% efficiency at 40% load and 55% efficiency at full load. These part load efficiencies indicate that it is plausible that the maximum efficiency decrease found in VRE-high, of 2pp for both coal and gas, is caused by increased part load operation due to VRE intermittency.

5 Discussion

The studies used in the literature research were mainly wind integration studies. The share of PV is unsubstantial and inferior to the increase in wind penetration in these studies. Taken into account that the generation profile is different for PV and wind, the results of the literature study may have a different effect on full load hours and efficiency of fossil-fired power plants compared to the results of this research, where some countries have relatively high VRE penetration (e.g. Italy 8.0% and Germany 5.7% in 2014). PV integration studies are available in literature but these were found to mainly focus on the effect of increased PV penetration on the electricity grid, as PV is mostly decentralised power generation in areas where the grid is not designed for transporting substantial amounts of electricity.

In calculation of the full load hours, autoproducers were included as the WEPP Database from Platts (2011) does not make a distinction between main activity electricity only and autoproducer plants. In energy efficiency calculations, however, autoproducers were excluded. This is due to autoproducer CHP plants where fuel input consists only of the part that is sold, not the part which is consumed within the autoproducer's establishment (InterEnerStat, 2016). This would generate higher efficiencies than in reality. Isolating the full load hours of a number of autoproducer plants to provide an indication of a percentage difference is not possible, as power generation data per power plant is not made public. Therefore no quantifiable effect of including the autoproducers in full load hours calculations can be given.

In the research, three VRE penetration groups were compared. The magnitude in terms of total electricity generation was however not evenly spread over the groups. In 2014, the electricity generated from fossil fuels was 160 TWh in VRE-high, 800 TWh in VRE-medium and 308 TWh in VRE-low. This means especially in VRE-high, and partially in VRE-low, the groups are more sensitive to deviations and fluctuations from a single country. However, a different division of countries within the three VRE penetration groups was not possible as the difference between the lowest VRE penetration country in VRE-high (Ireland, 19.5%) and the highest VRE-penetration country in VRE-medium (Germany 14.5%) was too large. The same for VRE-medium (Belgium, 10.3%) and VRE-low (Sweden, 7.3%). To avoid individual results of smaller countries being lost, the results of each individual country in VRE-high, the most relevant group for this research, were added in the Appendix.

In the WEPP Database from Platts (2011), two capacities per power plants or unit are listed, a lower and higher value described as *minimum capacity* and *maximum capacity*. The full load hour calculations were based on the higher capacity value as this is the value that plant owners use to indicate their power plant's capacity. However, this maximum capacity may in reality only be theoretically reached. The difference between minimum and maximum capacity varied between 0% and 6%, even though for the majority of the power plants the minimum and maximum capacities were the same.

The data from the WEPP Database which was used in this research was updated until 2011, while the calculations of full load hours were made until 2014. As explained in the methodology, national statistics were used for the larger countries (France, Germany, Italy, Netherlands, Spain and the UK) to determine the installed coal, gas and oil capacity from 2012-2014. These values were found to be deviating, especially for France (+31%) and Italy (+11%). This difference may be caused by more detailed knowledge of the power system by the national organization providing the statistics, for example power plants down due to maintenance or retrofitting or temporarily shut-down may not be recorded in Platts (2011) but are recorded in national statistics. If the national statistics of the two highest deviating countries (Italy in VRE-medium and France in VRE-low) would have been used for the period 2011-2014, this would results in a 3% lower fossil full load hours in VRE-medium and 5% lower fossil full load hours in VRE-low.

The power plants in Platts (2011) were categorised into coal-, gas- and oil-fired power plants based on their listed primary fuel. However, for some power plants, a secondary fuel was listed. For example, in some coal-fired power plants biomass was listed as secondary fuel. When this power plant is (partially) fuelled by biomass for a large period within a year, the electricity generated by the biomass is categorised under *other renewables*, while the capacity is categorized under coal. This will cause a negative effect on the full load hours of the coal-fired power plant, even though the power plant is not losing operating time. This effect could however not be accounted for as no input or output data is made public for individual power plants.

As mentioned in the methodology, the date of decommission and construction of power plants, listed in Platts (2011), is rounded off to the nearest year. A power plants with a construction date of June 30 in a year, is not counted for that year, even though it has been in operation for almost half a year. Taken into account that the majority of the decommission and construction dates is in January (around 95% obtained by random sample test), the decision was made to round off the dates to the nearest year for easiness in calculations.

The final discussion point regards the lack of registration of retrofits in power plants in Platts (2011). This specifically has an influence on the comparison and correlation of the trends average year of commission and efficiency. For example, an old coal-fired power plant constructed in 1970 is likely to have a corresponding low efficiency. But if the plant is retrofitted for example around 2010, the efficiency is most likely increased, possibly comparable to a modern power plant. However, this increased efficiency still corresponds to a power plant commissioned in 1970. This may have caused old coal-fired capacity to have relatively high corresponding efficiencies. Since no overview of power plants specific data on retrofits is made public, this effect was not taken into account in this research.

6 Conclusion

The trends in full load hours of the VRE penetration groups in this research showed that full load hours of fossil-fired power plants decrease more with a higher VRE penetration. After a stable period in fossil full load hours between 1990 and mid-2000s, the fossil full load hours decreased by 53% from 2006-2014 in VRE-high, by 31% from 2007-2014 in VRE-medium and by 26% from 2010-2014 in VRE-low. However, this decrease was found not to be solely caused by VRE penetration as the development of total electricity generation and non-VRE capacity were found to have a large influence on the decrease in full load hours. Only in VRE-high and VRE-medium, between 2010-2014, the decreasing fossil full load hours were found to be for the larger part caused by an increase in VRE penetration. In VRE-high the full load hours decreased from by 861 from 3,205 to 2,344, while VRE penetration increased from 17% to 25%. In VRE-medium the full load hours decreased by 892 within this period from 4,156 to 3,264, while VRE penetration increased from 5% to 13%. These decreases in fossil full load hours were found to be higher than fossil full load hours decreases found in literature for similar VRE penetration increases: 480 and 221 for a VRE penetration increase from 15% to 29% and from 4% to 13%, respectively. These differences may be caused by deviating conditions in the literature studies compared to conditions in VRE-high and VRE-medium.

The import + export was found to be likely dependent on a more dominant factor than VRE penetration, as the import + export as share of total electricity generation was highest in VRE-low. The import + export quantities are most likely dominantly affected by financial motives, meaning that countries trade (non-VRE) electricity with neighbouring countries based on electricity price to minimalize costs, instead of using import/export capacities for surplus of VRE.

The efficiency of coal- and gas-fired power plants was found to be very strongly dependent on the average year of commission. The only deviations in energy efficiency from the trend in average year of commission were found in VRE-high, where coal efficiency decreased from 40% to 38% and gas efficiency decreased from 54% to 52% between 2010-2014. These decreases were found to be most likely caused by the intermittency of VRE, causing increased start-ups and part load operation. Even though the effect of VRE on part load operation was not found in literature, the range in energy efficiency at different levels of part load operation were analysed in literature and together with the efficiency effect of increased start-ups indicated the efficiency decreases found in this research due to VRE to be plausible.

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8 Appendices

8.1 Appendix A

In Figure 42 the gas efficiencies are presented for EU member states, including both main activity as autoproducer plants, showing unrealistically high values for among others France, Spain, and Finland.

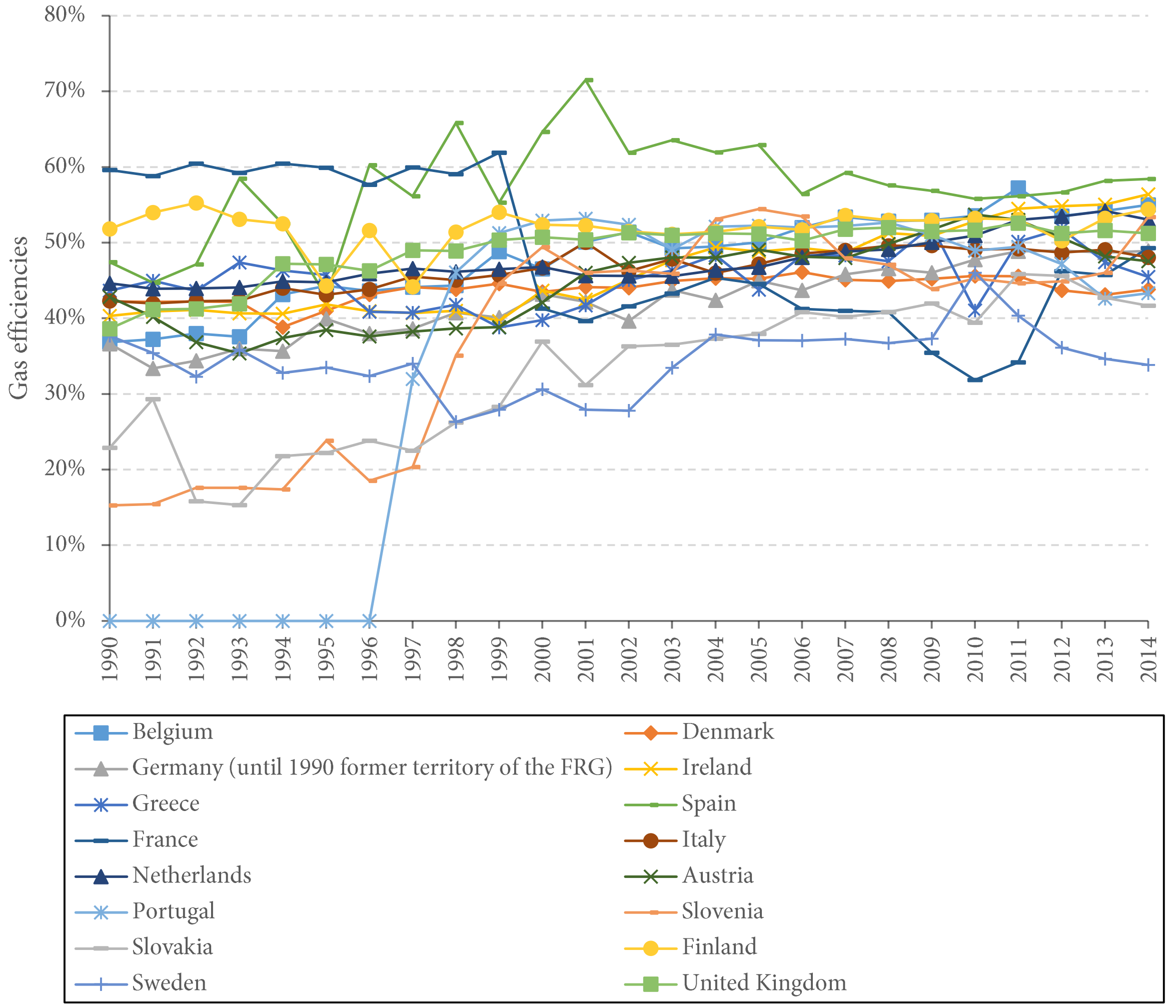

Figure 42: Gas efficiencies of main activity and autoproducers plants in EU member states.

8.2 Appendix B

In Figure 43 oil efficiencies of EU member states are presented, indicating unrealistically high efficiencies for among other Belgium, Germany, France and the UK.

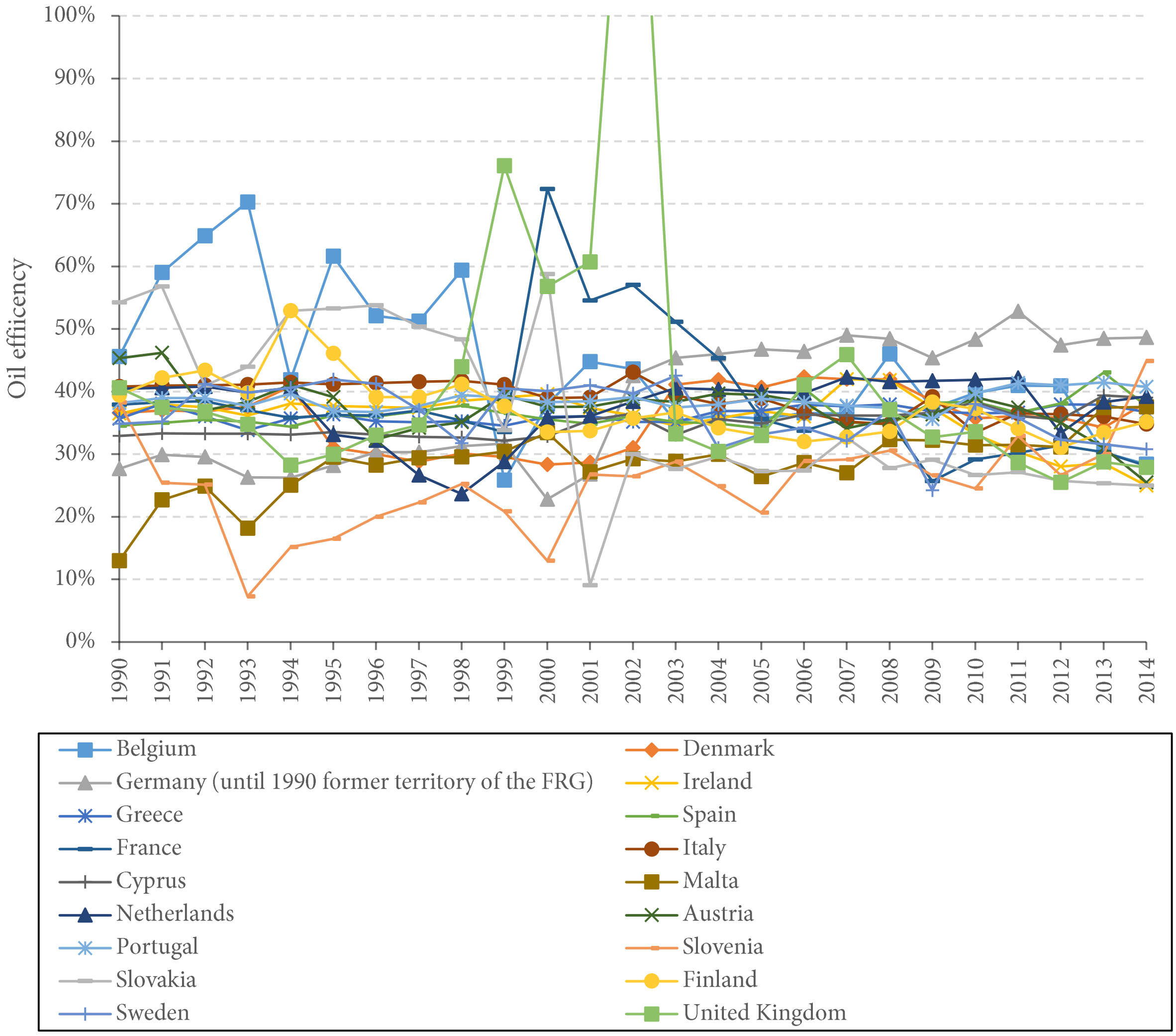

Figure 43: Oil efficiencies of EU member states, main activity producers only.

8.3 Appendix C

In Figure 44 and Figure 45 it can be identified that the trend of fossil full load hours is very much dependent on the trend in electricity generation. The trend in electricity generation fluctuates more than the total electricity generation trend in VRE-high due to the large import + export capacities of Denmark. Peaks in electricity generation comply with dips in net import in Figure 46, indicating high exports. From 2006-2014, the electricity decreased by 30% from 46 TWh to 32 TWh, while the non-VRE capacity decreased from by 16% from 10 GW to 8 GW. The VRE capacity increased by 67% from 3 GW to 5GW within this period. These three development caused a decrease in fossil full load hours from 3,920 to 1,605.

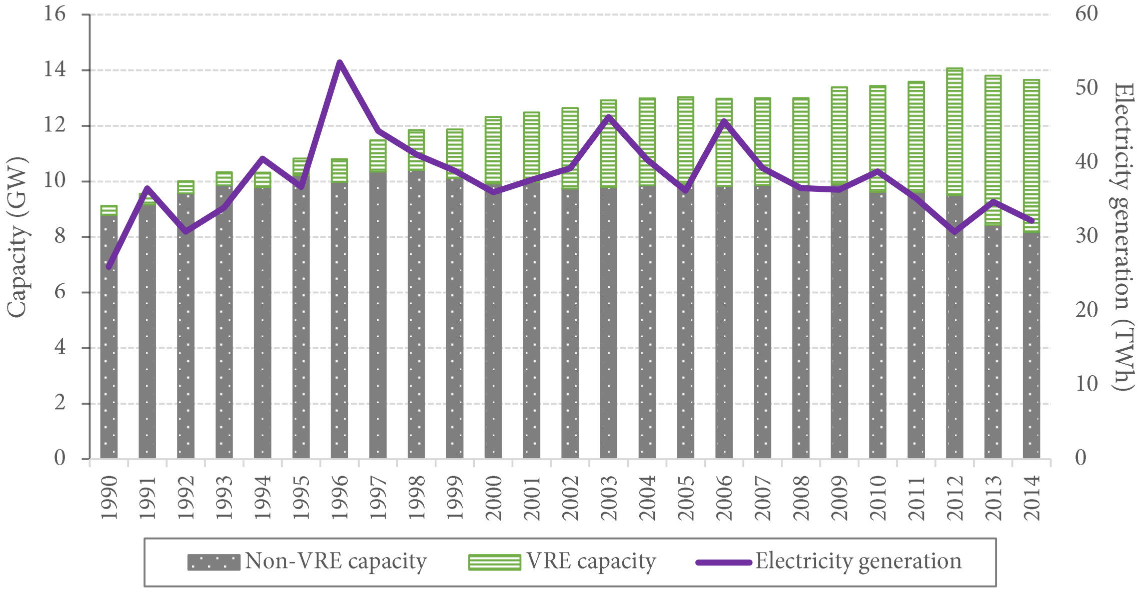

Figure 44: Non-VRE capacity, VRE capacity and electricity generation trends in Denmark.

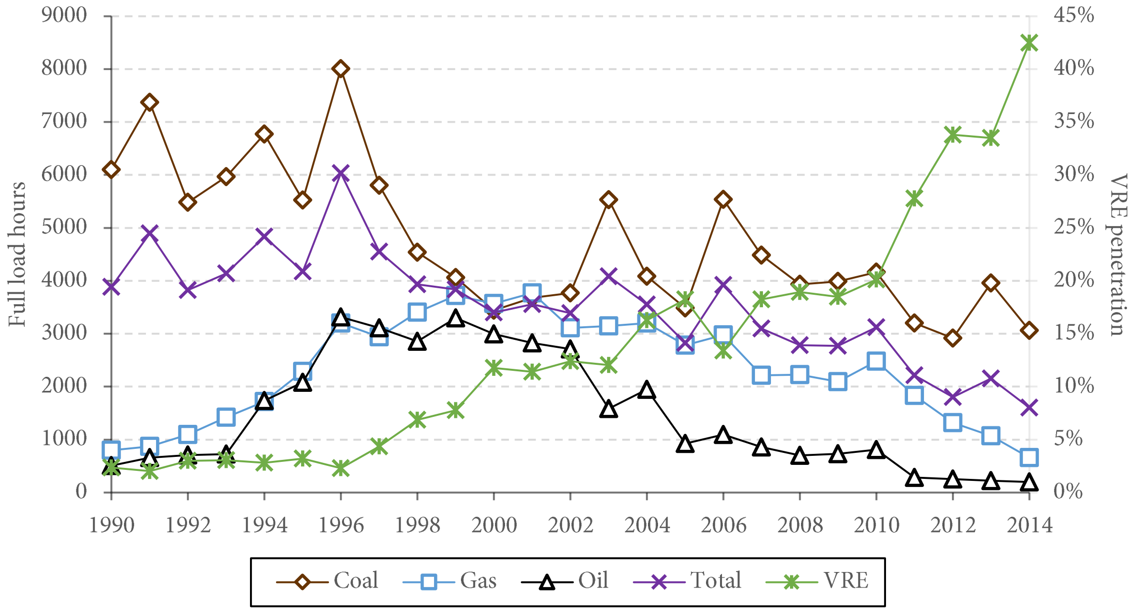

Figure 45: Full load hour and VRE penetration trends in Denmark.

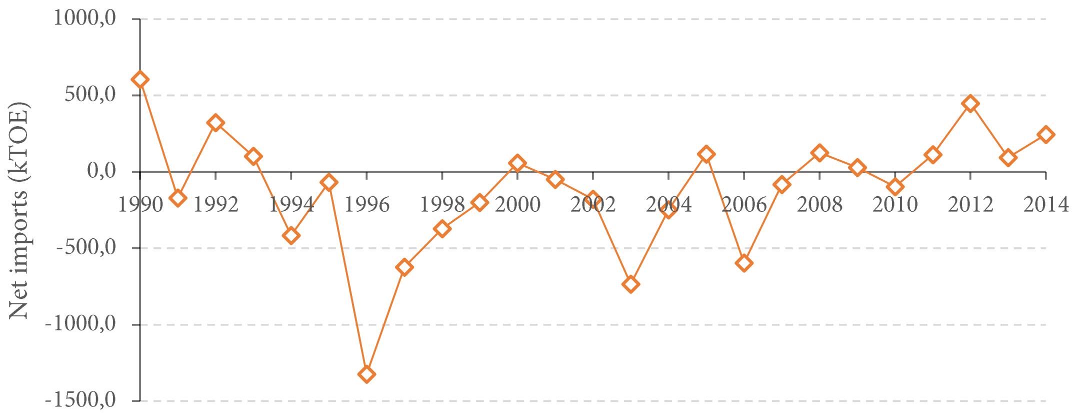

Figure 46: Net imports of Denmark.

In Figure 47 and Figure 48 the trends of Ireland are presented. From 2008-2014 the electricity generation decreased by 13% from 30 TWh to 26 TWh, while the non-VRE capacity increased by 10% from 6 GW to 7 GW. These two development, combined with a VRE capacity increase of 100% from 1 GW to 2 GW, caused a decrease in fossil full load hours from 4,666 to 3,075.

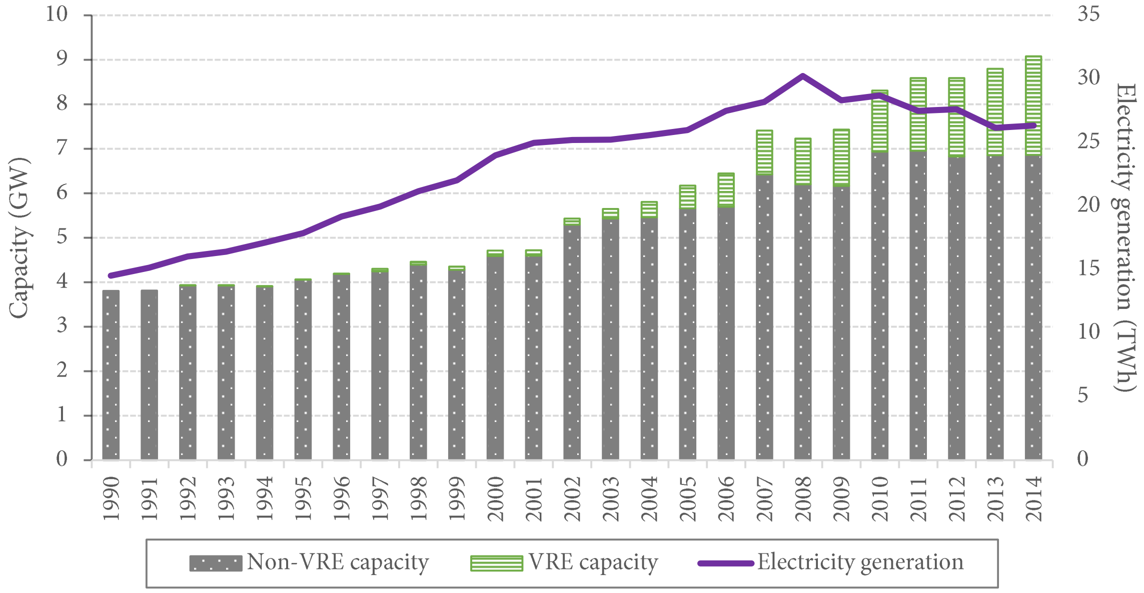

Figure 47: Non-VRE capacity, VRE capacity and electricity generation trends in Ireland.

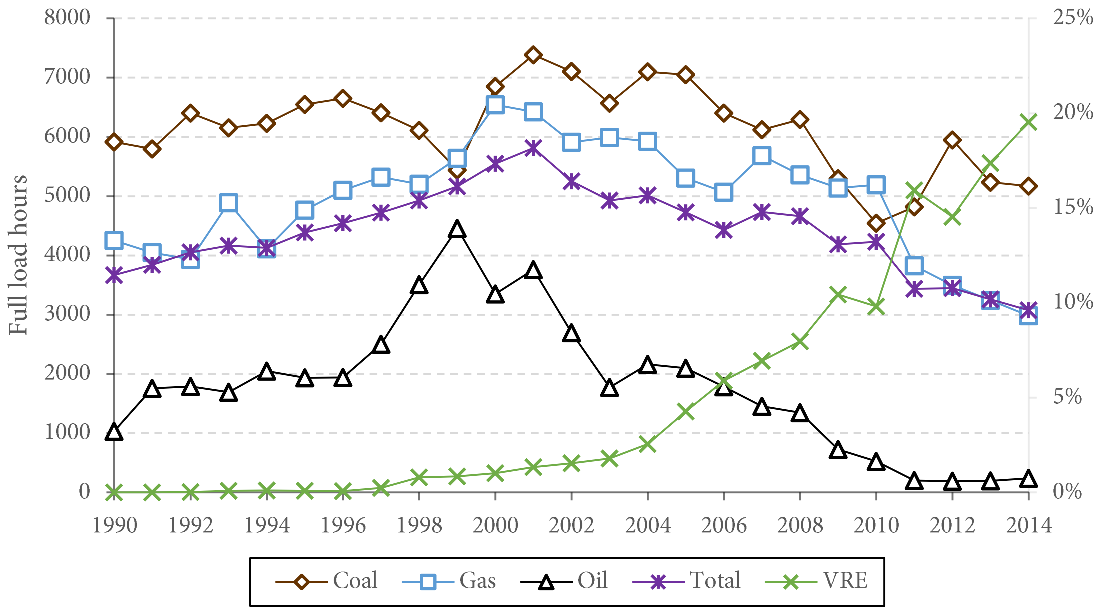

Figure 48: Full load hour and VRE penetration trends in Ireland.

In Figure 49 and Figure 50 the trends of Portugal are presented. The fossil full load hours have decreased from 5,971 in 2005 to 2,829 in 2014. Even though there are several increases and decreases visible within that time period, the overall electricity generation increases by 13% from 47 TWh to 53 TWh, the non-VRE capacity increases by 17% from 12 GW to 14 GW and the VRE capacity increases by 500% from 1 GW to 5 GW.

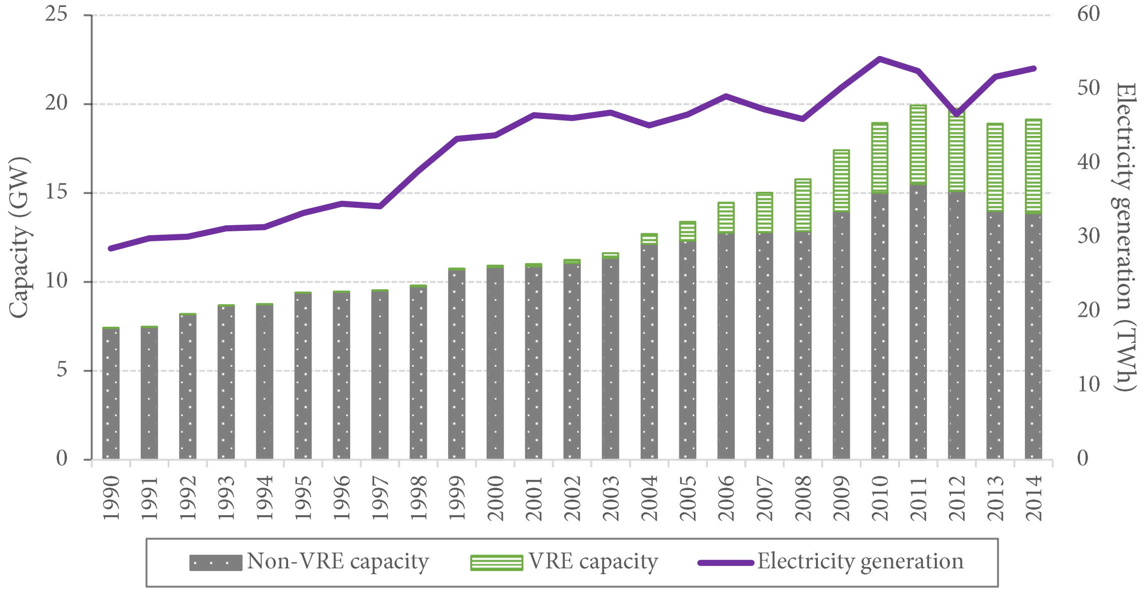

Figure 49: Non-VRE capacity, VRE capacity and electricity generation trends in Portugal.

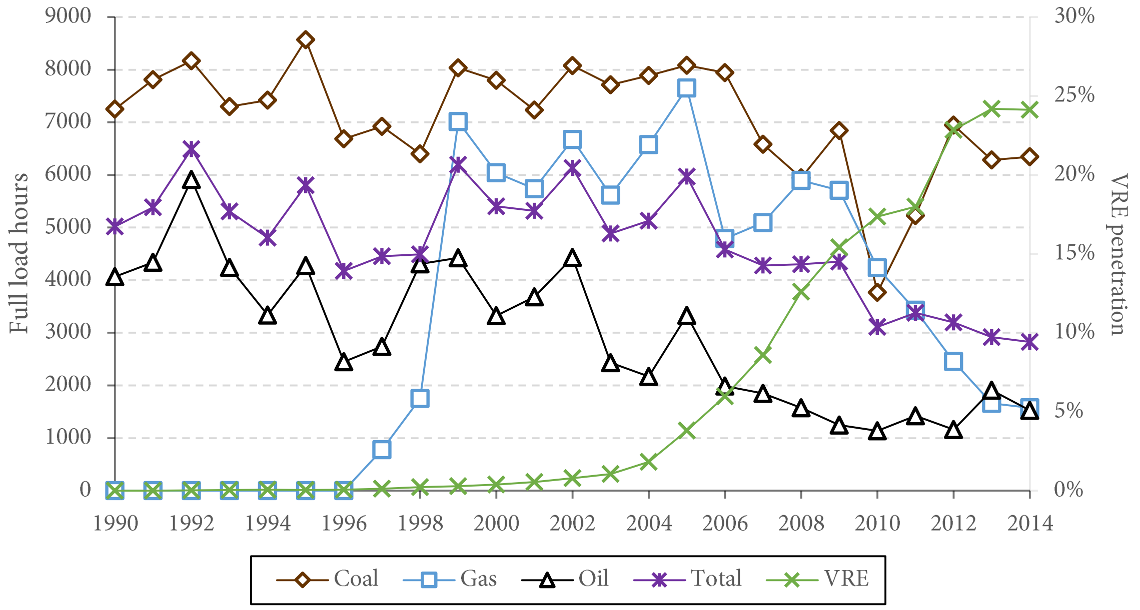

Figure 50: Full load hour and VRE penetration trends in Portugal.

8.4 Appendix D

In Figure 51, Figure 52 and Figure 53, correlations are calculated between import + export and VRE production for the three VRE penetration groups. All figures indicate very strong correlations.

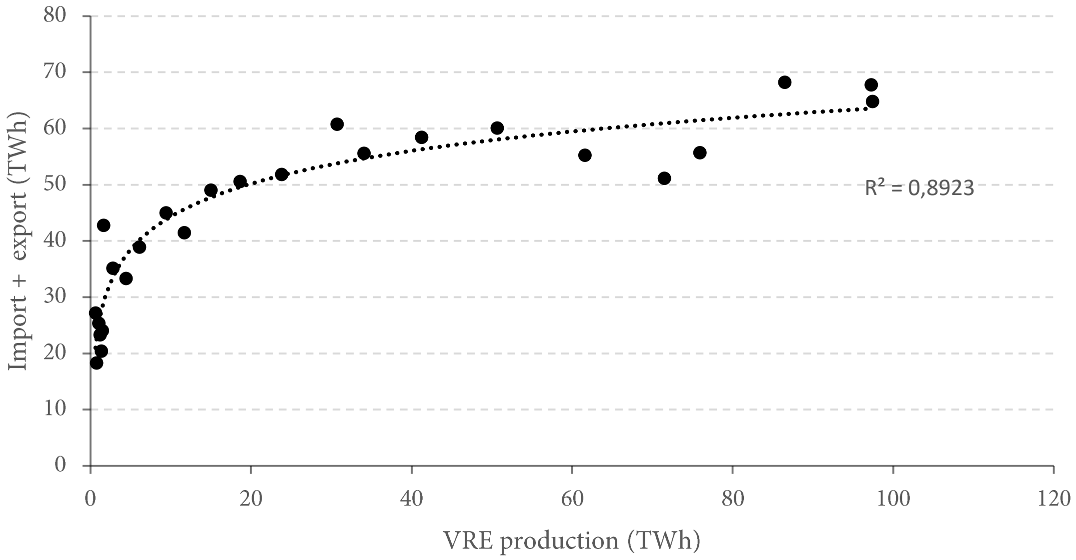

Figure 51: Correlation VRE and import + export in VRE-high.

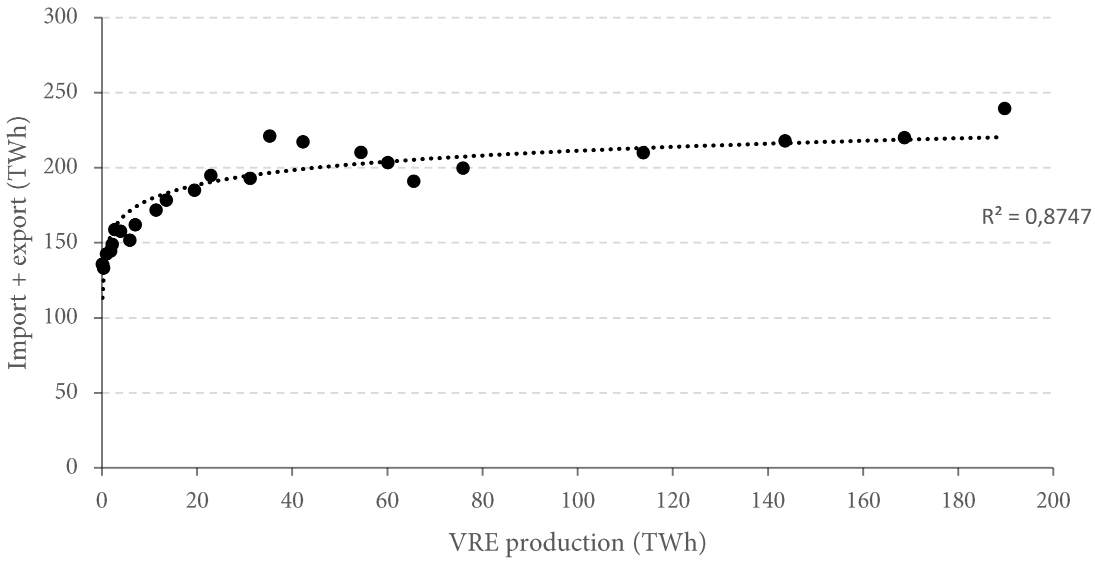

Figure 52: Correlation VRE and import + export in VRE-medium.

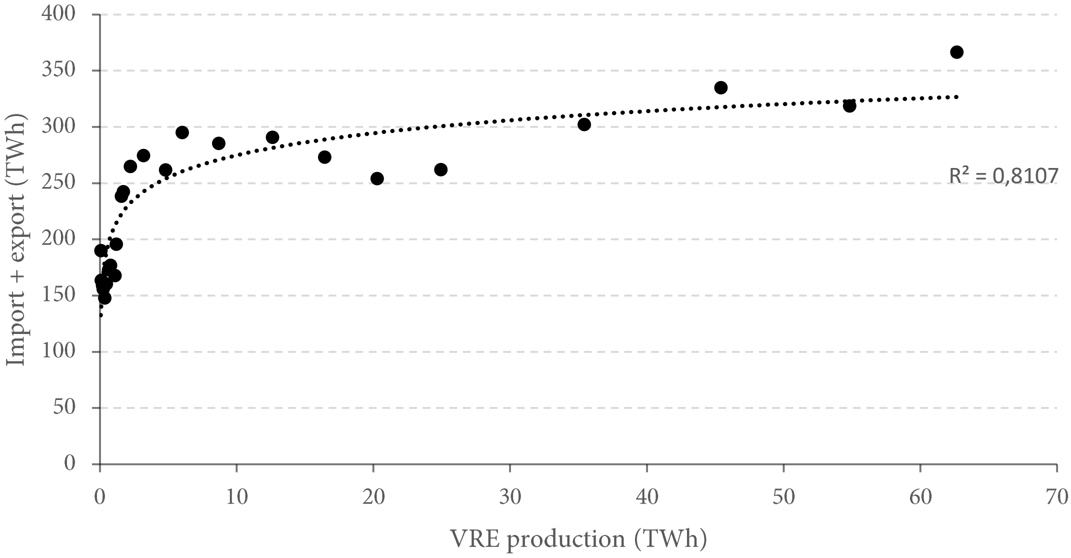

Figure 53: Correlation VRE and import + export in VRE-low.