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The effects of variable renewable electricity on energy efficiency and full load hours of fossil-fired power plants in the European Union

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ABSTRACT

This study focused on the effects of variable renewable electricity (VRE) on full load hours and energy efficiency of fossil-fired power generation in the European Union from 1990-2014. Member states were aggregated into three groups based on the level of VRE penetration. Average full load hours are found to be decreasing since 2006 for all groups. The decrease is most in the group with the highest VRE penetration level with a 53% decline from 2005 to 2014 (while VRE penetration increased from 8% to 25%). For VRE-medium the decrease was 34% from 2007 to 2014 (while VRE increased from 3% to 13%) and for VRE-low 32% (with 1% to 5% VRE penetration increase). Both the financial crisis and the share of VRE show strong correlations with full load hours. Both can explain the developments for VRE-high. For VRE-medium no significant relation with the recession was found and for VRE-low both factors were not significant. For energy efficiency, the commissioning year shows a strong correlation for natural gas and less for coal. Significant impacts are found for average commissioning year and full load hours on the energy efficiency of natural gas-fired power generation but not for coal.

1. Introduction

In 2014, as much as 27% of the European Union's greenhouse gas emissions were caused by the combustion of fossil fuels in public electricity and heat production [1]. In order to reduce greenhouse gas emissions and the accompanying climate change effect, the European Union (EU) aims for increased electricity production from renewable energy. Renewable electricity has increased over the last decade from a share of 14.4% in total gross electricity generation in 2004 to 27.5% in 2014 [1], and the projection for 2020 is 35% [2]. The current share of renewable electricity is not evenly spread over the EU member states. Based on data from Eurostat [1], 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%). EU-wide, hydropower is responsible for the highest share of renewable electricity (44% in 2014). However, the largest growth in the past ten years is visible in the expansion of wind power (from 1.8% in 2004 to 7.9% of total electricity generation in 2014) and photovoltaics (PV) (from 0.02% in 2004 to 2.9% in 2014). 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%) [1].

The variability in the electricity output of wind and solar energy technologies (e.g. PV and solar thermal power), caused by weather characteristics, has implications for transmission and distribution systems [3]. These characteristics can affect up to 70% of daytime solar capacity due to passing clouds, and 100% of wind capacity on calm days [4]. These uncertainties are much greater than the traditional uncertainties of a few percent in demand forecasting. Intermittency of variable renewable electricity (VRE) sources becomes increasingly difficult to manage as their penetration levels increase [5]. Currently, renewable energy variability is generally compensated by fossil-fired power plants being started-up and-shut down, ramped up and down, and operated at part load levels more frequently [6–9]. This impacts the year-round average energy efficiency of these plants, which achieve maximum efficiency when they operate at full load [10]. Especially older coal-fired power plants tend to have limited operational flexibility and cycling to operating at part load levels and increased start-ups of these power plants results in a lower energy efficiency due to the increased fuel consumption [11].

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Table 1
Summary of full load hour studies (CCGT, combined cycle gas turbine; GT, Gas Turbine).

Study	Scenario	VRE%	Coal (h/yr)	CCGT (h/yr)	GT (h/yr)
Southwest Power Pool	Base case	4%	7183	5606	n/a
Wind Integration Study	Scenario 1	10%	7008	4818	n/a
[5]	Scenario 2	20%	6658	4117	n/a
New York ISO Wind	Base case	4%	7350	5519	2374
Integration Study	Scenario 1	13%	7271	5046	2059
[12]	Scenario 2	19%	7174	5046	1927
	Scenario 3	25%	7174	4809	1971
7.55 GW Study	Base case	15%	6570	6920	n/a
[11]	Scenario 1	29%	6044	6395	n/a
	Scenario 2	43%	5782	5256	n/a
9.6 GW Study	Base case	11%	7008	7621	n/a
[11]	Scenario 1	23%	6658	7183	n/a
	Scenario 2	34%	6482	6482	n/a

In this study we look at how increasing VRE penetration (i.e. share of VRE in the total electricity generation) has affected the full load hours and energy efficiency of European fossil-fired power plants. This will provide insight into the effect of VRE on the performance of fossil-fired power plants. A number of studies are present that estimate the effect based on modelling [5,11,12] but, to our knowledge, there is no study which looks at what the actual effects have been so far. We do this by first reviewing literature in order to determine what the effect of VRE on the performance of fossil-fired power plants is according to modelling studies. Then we analyse the development of full load hours and energy efficiency of fossil-fired power plants in the EU[1] in the years 1990–2014, as this period shows the emergence of significant levels of wind and solar in many member states.

The paper is structured as follows. Section 2 presents effects of VRE on full load hours and energy efficiency, as found in literature. Section 3 describes the method used and section 4 gives the results of this study. Section 5 contains the discussion of uncertainties and lastly, section 6 gives conclusions.

2. Impact of VRE on full load hours and energy efficiency found in literature

In this section we first discuss the impact of VRE on full load hours of fossil-fired power plants, as found in literature sources (2.1), and second the possible impact of load hours on the energy efficiency of fossil-fired power plants (2.2).

Energy efficiency of power generation refers here to the ratio of yearly electricity output of a power plant and primary energy input. This is a year-round average efficiency. The efficiency is significantly affected when plants operate under off-design conditions, such as part-load operation and shut downs [13]. Both are reflected in the number of full load hours of a power plant. This is defined as the total electricity output in a year (in GWh) divided by the installed capacity (in GW).

2.1. Impact of VRE on full load hours

Table 1 shows the effect of increased VRE penetration on full load hours of fossil-fired power plants as found in available studies. Multiple scenarios are included with increasing levels of VRE penetration and a base case. These studies all show a decrease in full load hours with increasing VRE penetration level. In general, the decrease in full load hours of coal-fired power plants is lower compared to gas-fired power plants. The highest decrease for gas-fired power plants was 27% when VRE penetration increased from 4% to 20% [5]. The highest decrease for coal-fired power plants was 12% with increasing VRE penetration from 15% to 43% [11].

2.2. Impact of VRE on energy efficiency

The lower full load hours due to increased VRE penetration can have an impact on the average annual energy efficiency by increased part load operation and more start-ups/shut downs. Direct effects of increased VRE on energy efficiency due to part load operation are not available in literature. However, part load efficiency curves can provide an indication of the range of the effect of part load operation. Figs. 1 and 2 show available part load curves for coal and gas-fired power plants, respectively. The figures show that part load operation could impact efficiencies by typically up to 3–8 percent point (pp) for most coal-fired power plants (although up to 19 pp may occur for IGCC power plants) and 10-17 pp for most gas-fired power plants (up to 23 pp possible for a gas turbine), depending on the power plant type and the degree of part load operation.

The amount of fuel used for start-up of a power plant depends on the status of the power plant. If a power plant has been shut-down less than 8–12 h ago, it is referred to as a hot start, between 12 and 48 h as a warm start, and between 48 and 120 h or more as a cold start [18]. The longer the downtime, the higher the fuel consumption will be during start-up. In Table 2, two studies are listed in which the effect of a 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 energy efficiency of the power plants by using start-up fuel consumption data from Kumar et al. [19]. In order to do so, the energy efficiency of coal-fired and CCGT power plants are assumed to be 43% and 55%, respectively, reflecting the average of the energy efficiency curves. For each scenario, a range of energy 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. The studies model that a significant increase in VRE affects the amount of start-ups per year. However, the relative impact on overall energy efficiency is calculated to be low, with a maximum effect of 0.5 pp for gas-fired power plants (CCGTs) and 0.3 pp for coal-fired power plants. Since only two studies were found, the results cannot be generalized and in reality the effect may be different, depending on the number of increased start-ups.

[1] In this research the EU-27 is analysed instead of EU-28, as one of the available databases did not include the most recent member state Croatia, which joined the EU in 2013. The electricity generation of Croatia in 2014 was equal to 0.4% of the EU-27's electricity generation. The effect of excluding Croatia in the results is therefore considered negligible.

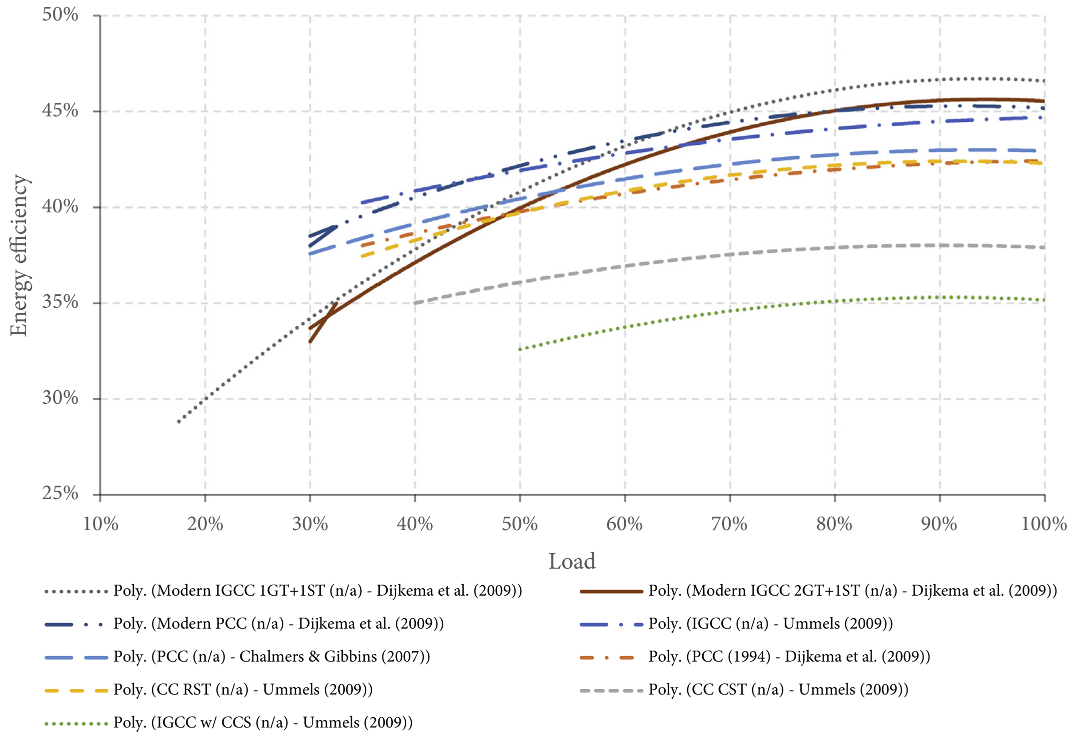

Fig. 1. Part load efficiencies of coal-fired power plants, construction year in brackets (Chalmers and Gibbins, 2007 [14]; Dijkema et al., 2009 [15]; Ummels, 2009 [16]). (PCC, Pulverized Coal Combustion; GT, gas turbine; IGCC, integrated gasification combined cycle; ST, Steam Turbine).

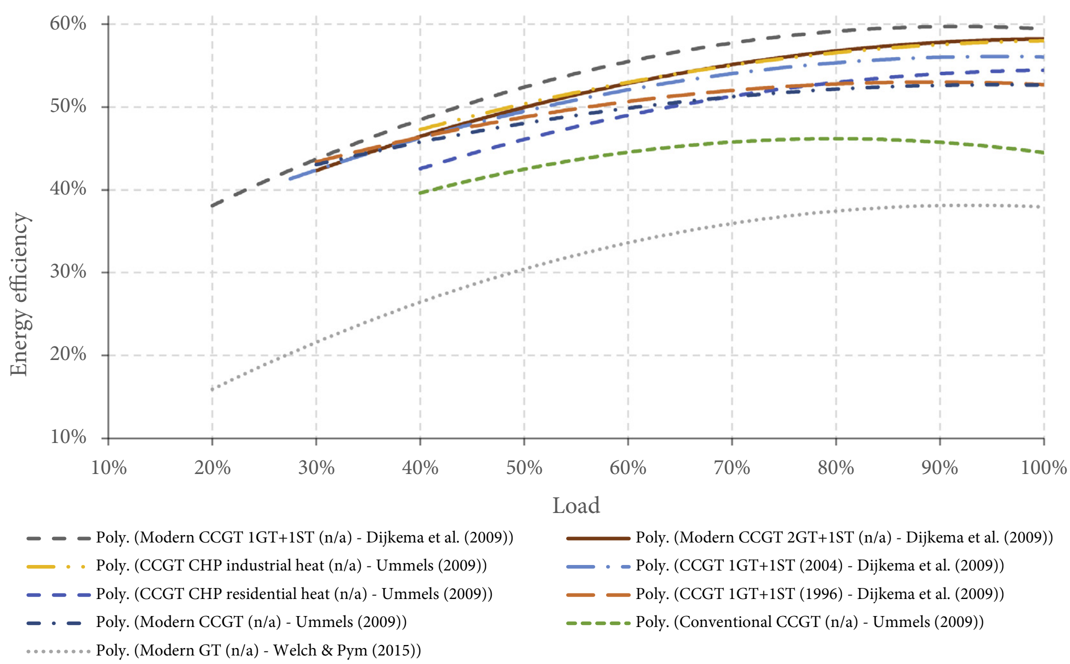

Fig. 2. Part load efficiencies of gas-fired power plants, construction year in brackets (Dijkema et al., 2009 [15]; Ummels, 2009 [16]; Welch and Pym, 2015 [17]). (CCGT, combined cycle gas turbine; ST, Steam Turbine; GT, Gas Turbine; CHP, combined heat and power).

3. Methods

This section provides an overview of the methods applied in this study:

- Calculation of the VRE penetration for each EU member state per year between the timeframe of 1990–2014 (3.1).
- Calculation of full load hours of coal-, gas-, oil-fired power plants and total fossil-fired power plants (3.2).
- Calculation of the energy efficiency of electricity generation (3.3)

Table 2
Energy efficiency effects in percentage points (pp) caused by start-ups (CCGT, Combined-Cycle Gas Turbine).

Study	VRE	Plant	Delta start-ups per year (nr)	Effect on energy efficiency (pp)
[11]	15% → 43%	Gas (CCGT)	50	−0.2 to −0.5
7.55 GW peak demand scenario		Coal	−5	0.06 to 0.03
[11]	11% → 34%	Gas (CCGT)	55	−0.2 to −0.5
9.5 GW peak demand scenario		Coal	5	−0.03 to −0.06
[7]	0% → 34%	Gas (CCGT)	12	−0.1 to −0.2
		Coal	12	−0.2 to −0.3

- Correlation and regression analysis (3.4).

3.1. VRE penetration

For each EU member state, the VRE penetration for each year in the period 1990–2014 was calculated by formula (1).

$$\text{VRE penetration}_{\text{year i} \ldots \text{N}}\,(\%) = ((E_W + E_{PV} + E_{STh})/E_{TOT})_{\text{year i} \ldots \text{N}} \quad (1)$$

where E_W is the gross electricity generation from wind; E_{PV} is the gross electricity generation from solar photovoltaics; E_{STh} is the gross electricity generation from solar thermal; E_{TOT} is the total gross electricity generation from all sources, both renewable and non-renewable; year i = 1990, year N = 2014.

Based on the VRE penetration in 2014, three groups were made in which countries were aggregated to form a group with high (15%+), medium (7.5%–15%) and low (0%–7.5%) penetration VRE, presented in Fig. 3. The groups will be referred to from this point onwards as VRE-high, VRE-medium and VRE-low. At the start of the timeframe in 1990 the VRE penetration was negligible in almost all countries, except Denmark, where the VRE penetration was 2%.

The reason to form groups is to be able to compare developments in fossil full load hours and energy efficiency for only three groups instead of individual countries. Also the effect of coincidences in single countries is reduced when comparing the three VRE penetration groups and make the results more robust. The aggregation is based on weight, meaning that countries with high electricity generation have a higher impact on the results of a VRE penetration group compared to countries with low electricity generation. In general, small countries may compensate VRE output more easily with import and export and thereby limit the effect of VRE intermittency on fossil-fired power plants.

3.2. Full load hours

The full load hours (FLH) per year and per VRE penetration group were calculated for each fuel type separately and for fossil fuels in total (see formula (2) and (3) respectively). Besides the aggregated full load hours of fossil-fired power generation also coal- and gas-fired power generation were calculated separately since the impact of VRE on FLHs is expected to be different per fuel. Oil-fired power generation was not included individually since it only accounted for 2% of electricity generation in the EU in 2014.

$$FLH_x\,(\text{hours})_{\text{year i} \ldots \text{N}} = (E_x/C_x)_{\text{year i} \ldots \text{N}} \quad (2)$$

$$FLH\,(\text{hours})_{\text{year i} \ldots \text{N}} = (FLH_{coal}{}^{*}C_{coal} + FLH_{gas}{}^{*}C_{gas} + FLH_{oil}{}^{*}C_{oil})/(C_{coal} + C_{gas} + C_{oil})_{\text{year i} \ldots \text{N}} \quad (3)$$

where x is coal, oil or gas; FLH full load hours; E is gross electricity generation in GWh per fuel; C_x are the total installed capacities of the fossil fuel plants; year i = 1990, year N = 2014.

The electricity generation per fossil fuel was obtained from Eurostat [1]. The capacity input data was obtained from the UDI World Electric Power Plants (WEPP) database [20]. This database contains all power plants in the EU. The individual power plants were divided into the three fuel types based on their listed primary fuel in the WEPP database. For each power plant the database indicates the commissioning and if applicable, decommissioning date. Most power plants had a commissioning date of 1 January. For the others, 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

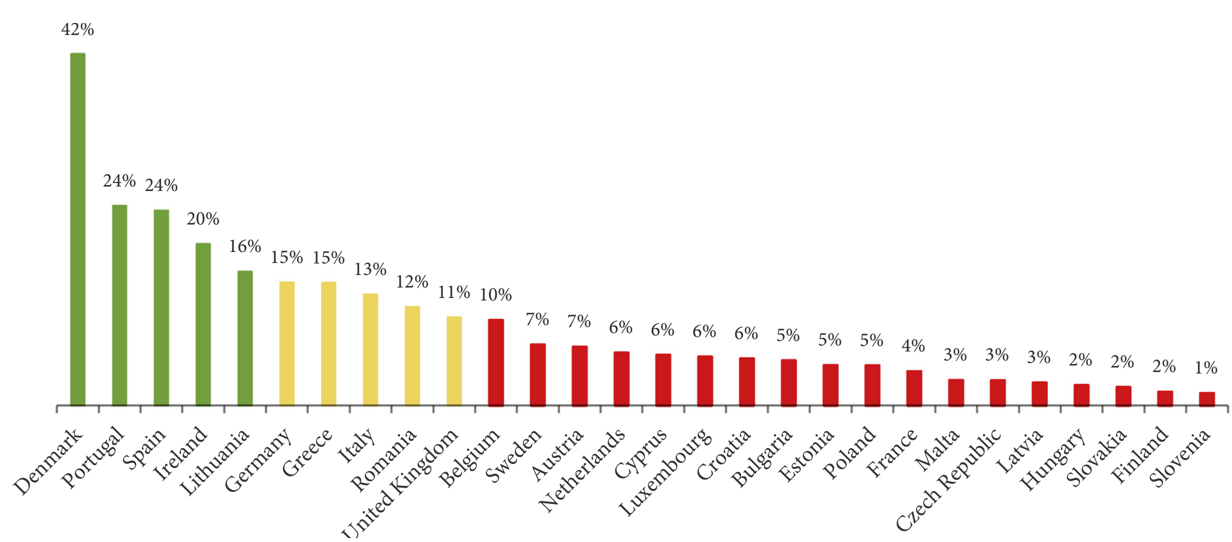

Fig. 3. VRE penetration of EU-27 countries in 2014 [1].

plant decommissioned on July 1, 2010 was considered to be online for the whole year 2010.

The WEPP database provided for this research is updated until 2011. For the countries Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, Greece, Hungary, Ireland, Latvia, Lithuania, Luxembourg, Malta, Poland, Portugal, Romania, Slovakia, Slovenia and Sweden the decommissioned and newly constructed power plants were manually edited and added to the database based on press statements and news articles. For larger countries (France, Germany, Italy, The Netherlands, Spain and the United Kingdom), national statistics and other sources, were consulted to determine the capacities between 2012 and 2014 (RTE [21], Fraunhofer ISE [22], Terna [23], TenneT [24], REE [25] and Carbon Brief [26], respectively).

3.3. Energy-efficiencies

The method for calculating the energy efficiencies per fossil fuel and VRE group was based on Graus et al. [27] (see formula (4)). Autoproducer plants were not included in the energy efficiency calculations as it was assumed that these plants mostly do not adjust their power output depending on VRE generation.

$$\textit{Energy efficiency}\ (\%)_{\text{year i} \dots \text{N}} = ((E + H^{*}s)/I)_{\text{year i} \dots \text{N}} \tag{4}$$

where E is the gross electricity output from main activity power and CHP plants; H is the heat output from main activity CHP plants; s is the correction factor between useful heat and electricity (power loss factor); I is the fuel input in lower heating value; year i = 1990, year N = 2014.

The correction factor "s" represents the typical electricity production lost per unit of useful heat extracted from CHP plants. This formula thereby gives the estimated energy efficiency, without heat output. Main activity CHP plants are assumed to dominantly deliver space heating to cities. According to Phylipsen et al. [28], for space heating based district heating schemes the correction factor varies between 0.15 and 0.2. Therefore, similar to the energy efficiency calculation in Graus and Worrell [10], in this research a value of 0.175 was used. The input data was obtained from Eurostat [1].

3.4. Correlation and regression analysis

In order to assess which factors played a role and to what degree in the development of FLH and energy efficiency, Pearson's correlation coefficients were calculated and linear regression analyses were performed. Fig. 4 shows a causal diagram of the main impacting factors on full load hours of fossil-fired power plants and energy efficiency. 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 electricity generation regards the electricity generation for the whole country, and the SRMC concerns the cost of single power plants (e.g. coal-fired, gas-fired, nuclear etc.).

Electricity generation, 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 electricity generation (due to lower demand) will decrease the full load hours of fossil-fired power plants, assuming the non-VRE capacity and VRE penetration remain constant. Electricity generation can have an impact on full load hours especially when it is different from expectations. The planning for new power plants starts many years before the commissioning and is based on expectations for electricity demand. Related to the economic recession, electricity demand has been lower than expected, leading to overcapacity in the electricity market. In order to take this effect into account we calculated the yearly growth rate of Gross Domestic Product (GDP) in the period 1990–2006 and used this to estimate the GDP development without recession (called corrected GDP) (see formula (5)). Data for GDP were taken from European Commission [29] and calculated per VRE penetration group.

$$\textit{Recession indicator}_{\text{ year i} \dots \text{N}} = (\text{GDP corrected/GDP})_{\text{year i} \dots \text{N}} \tag{5}$$

where GDP: Gross Domestic Product in market exchange rates and 2010 prices; year i = 2007, year N = 2014.

We also took into account the electricity demand development per VRE penetration group, based on Eurostat [1].

The Short-Run Marginal Costs (SRMC) of individual power plants affect the degree to which these power plants are utilized. For fossil-fired power plants, these are mainly influenced by fuel prices. E.g. low coal prices compared to natural gas prices can reduce the operation time of gas-fired power plants. Here we therefore included the natural gas price (for Europe in US$/GJ) and coal price (average price of Colombian, Australian and South African coal in US$/GJ). Both are in 2010 prices and taken from World Bank [30].

Increased imports and exports can limit the impact of VRE's variability on FLHs. For instance neighbouring countries relieved the German grid by consuming excess electricity generated from variable renewable sources [31]. Also pumped hydropower storage, widely available in Norway where the total storage capacity is equal to 70% of the annual electricity generation [32], can be used for reacting to sudden changes in variable renewable energy output within the region [33]. Since both imports (when VRE is low) and exports (when VRE is high) can be used to compensate for variabilities, these were both added up and divided by gross electricity generation as indicator (see formula (6)). This is not to be confused with the concept of net imports where exports are subtracted from imports to calculate the net amount of electricity consumption originating from outside of the country. Data for imports and exports per VRE penetration group were obtained from European Commission [29].

$$\text{Import} + \text{Export}\ (\%)_{\text{year i} \dots \text{N}} = (\text{Import} + \text{Export})/E_{\text{ year i} \dots \text{N}} \tag{6}$$

where E is gross electricity generation; year i = 1990, year N = 2014.

Year-round average energy-efficiency is mainly impacted by power plant characteristics, such as capacity age, fuel type, part-load operation and biomass co-firing. The average age of power plants was taken into account by the average commissioning year of the power plants based on Platts [20] weighted by capacity size (MW). Retrofitting can increase the energy-efficiency of older power plants but since no information is available for the amount of capacity retrofitted this factor is not taken into account. Also biomass co-firing in coal-fired power plants, which may decrease the energy-efficiency, is not included due to lack of data. The impact is expected to be limited since the share of biomass in electricity generation is only 5% of total electricity generation, while coal accounts for 25% [1].

4. Results

In this section the results for the three VRE penetration groups are discussed. These are split into full load hours and energy efficiency, after which the results of this study are compared with the results found in literature.

4.1. Full load hours

In Fig. 5 the full load hours and VRE penetration are presented of

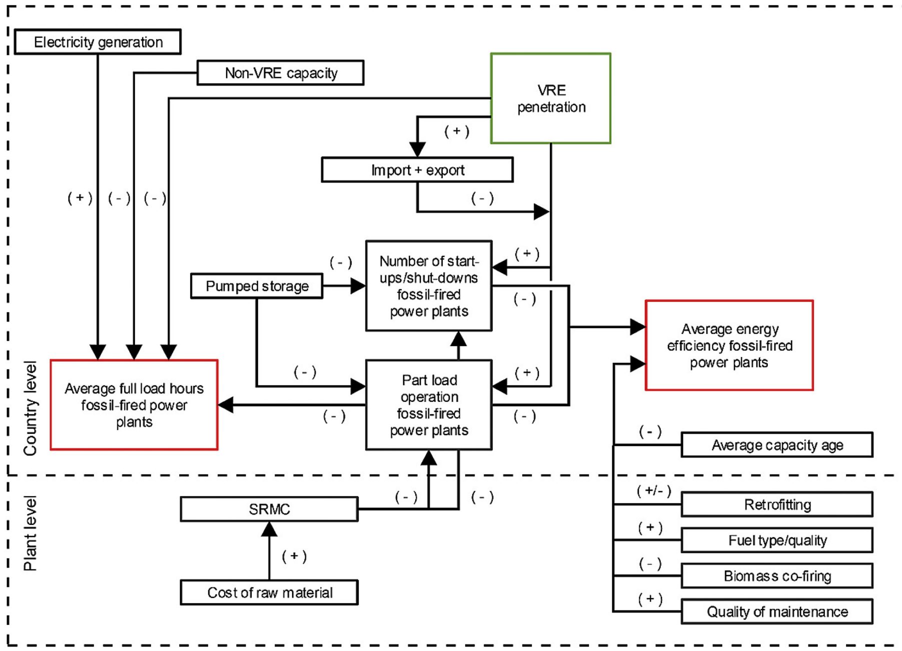

Fig. 4. Causal diagram between VRE penetration (green) and full load hours and energy efficiency (red). (SRMC, Short-Run Marginal Costs). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

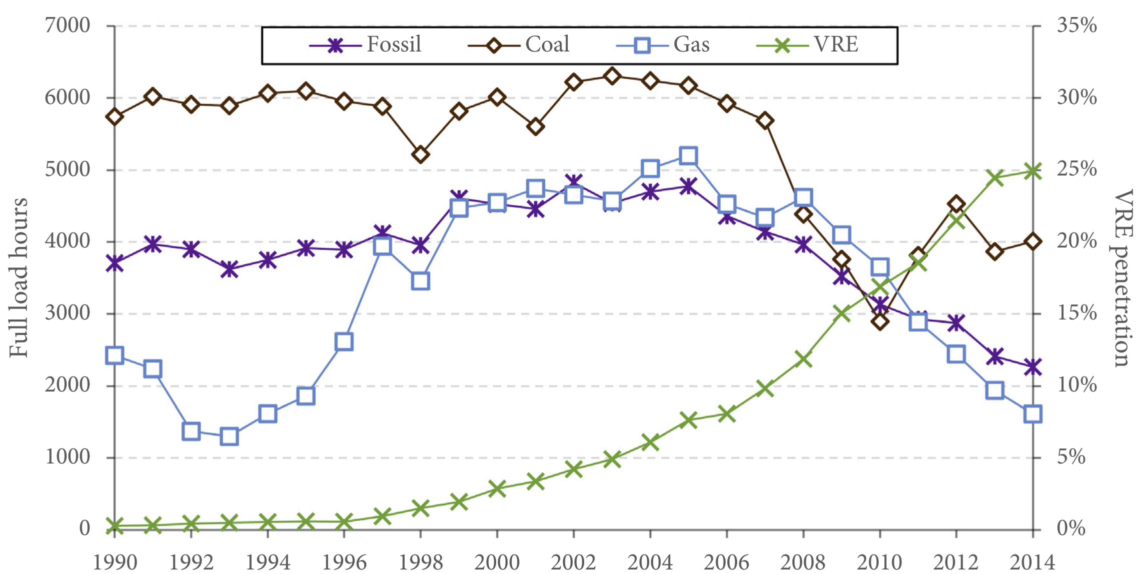

Fig. 5. Full load hours trends and VRE penetration of VRE-high.

VRE-high and Fig. 6 shows the trends in electricity generation, installed non-VRE capacity and installed VRE capacity. The fossil full load hours decreased by 53% from 4773 hours in 2005 to 2264 in 2014, while VRE penetration increased from 8% to 25%. The fossil full load hours slightly increased in the period 1990–2005, mainly caused by the increase in full load hours of gas-fired power plants. Around 1990 the capacity of gas-fired power plants was limited and most of the installed gas-fired power plants were peaking units, from 1994 onwards the gas-fired capacity increased rapidly and base load units were added to the landscape. From 2005 to 2010 most of the fossil full load decrease was caused by coal-fired power plants, of which the average full load hours decreased by 54% from 6173 in 2005 to 2897 in 2010. After 2010, the load hours of coal-fired power plants increased while those of gas-fired power plants continued to decrease by 56% from 3654 in 2010 to 1613 in 2014. Fig. 6 shows that electricity generation reached its maximum in 2008, after which it decreases from 440 TWh to 394 TWh in 2014, a decrease of 11%. The non-VRE capacity remained more or less constant in this period at 108 GW, while the VRE capacity increased rapidly from 27 GW to 43 GW, equal to an increase in VRE penetration from 12% to 25%.

In Fig. 7 the development of full load hours in VRE-medium are presented and Fig. 8 shows the development of electricity generation, VRE and non-VRE capacity. From 1990-2007 the fossil full load hours remained more or less constant. However, within this timeframe the introduction of gas-fired power plants utilized as

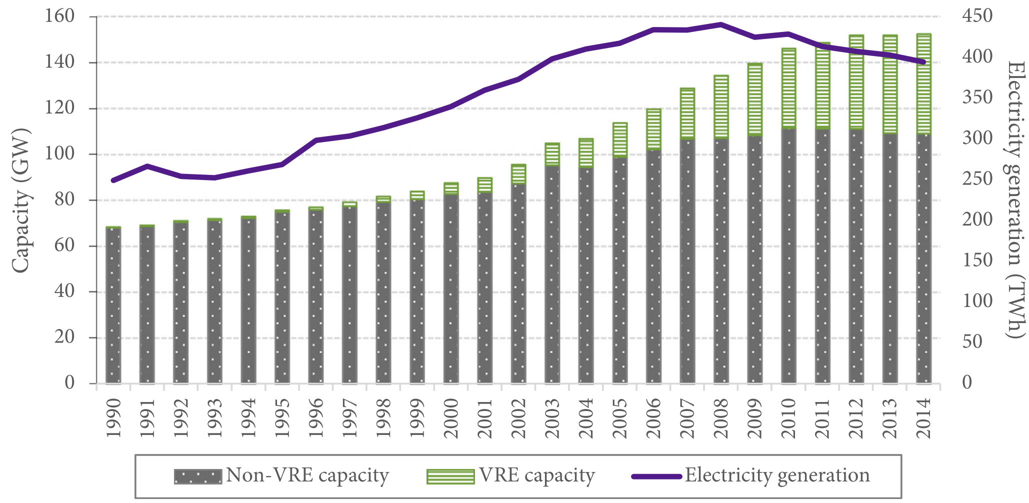

Fig. 6. Electricity generation, non-VRE and VRE capacity trends of VRE-high.

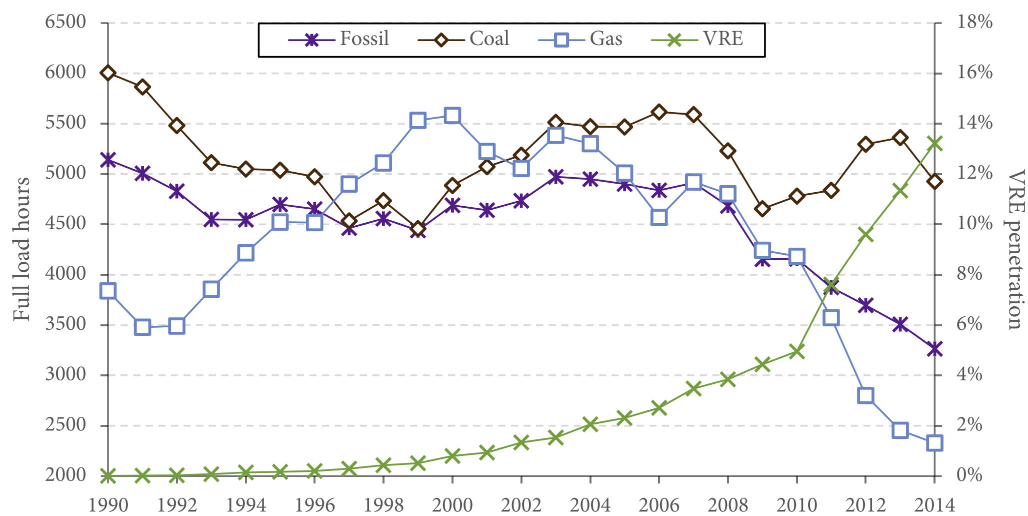

Fig. 7. Full load hour trends and VRE penetration of VRE-medium.

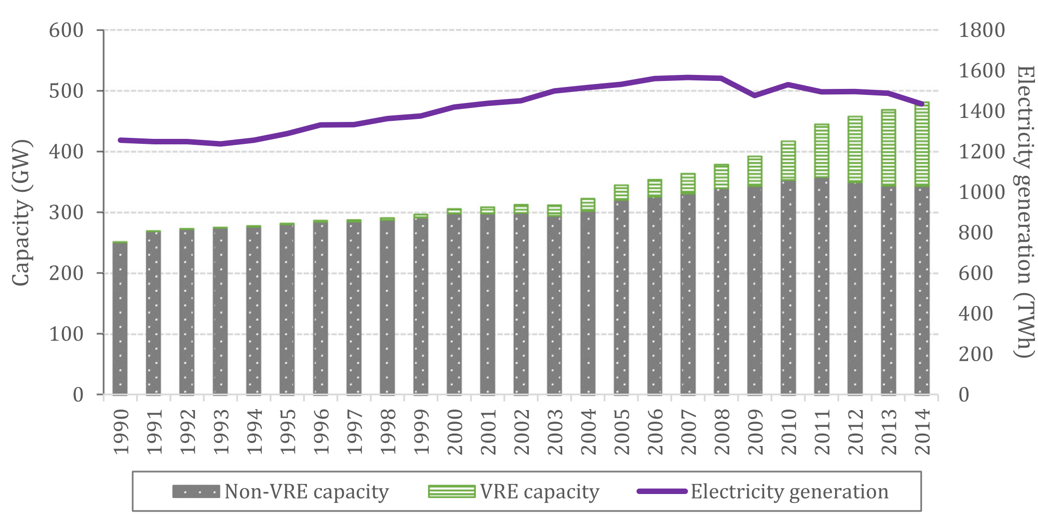

Fig. 8. Electricity generation, non-VRE and VRE capacity trends of VRE-medium.

base load units is visible. This caused the full load hours of gas-fired power plants to increase and the full load hours of coal-fired power plants to decrease, of which the total installed capacity remained more or less constant between 1990 (104 GW) and 2007 (101 GW). From 2007 onwards the fossil full load hours decreased from 4921 hours to 3264 in 2014 (by 34%). This decrease in fossil full load hours was mainly caused by gas-fired power plants, of which the full load hours decreased from 4921 in 2007 to 2329 in 2014 (53%). The average full load hours of coal-fired power plants fluctuated between the whole period of 1990–2014 around 5000. Fig. 8 shows that electricity generation reached its maximum in 2007 at 1565 TWh. The electricity generation decreased by 8.3% to 1435 TWh in 2014. Similar to VRE-high, 2008 acts as a turning point, as electricity generation started decreasing from this year onwards, related to the financial crisis. Within this same period, the non-VRE capacity fluctuated but ended at the same level in 2014 as in 2007, around 340 GW. The VRE capacity however, increased significantly from 33 GW in 2007 to 137 GW in 2014, equal to a VRE penetration increase from 3% to 13%.

In Fig. 9 the development of the full load hours of the last VRE penetration group, VRE-low, are presented and in Fig. 10 the electricity generation, non-VRE capacity and VRE capacity. The fossil full load hours decreased by 32% from 4379 in 2007 to 2961 in 2014, mainly allocated to a 51% decrease in gas-fired capacity use from 4881 full load hours in 2008 to 2433 in 2014. The average full load hours of coal-fired power plants decreased by 23%, from 4883 in 2007 to 3768 in 2014. Within the timeframe of 2007–2014, where fossil full load hours were found to decrease, the electricity generation remained roughly constant around 1335 TWh. In this VRE penetration group, the effect of the financial crisis is only clearly visible in the year 2008. After 2008 the electricity generation restored to pre-2008 levels. The non-VRE capacity increased slightly from 282 GW to 294 GW and the VRE capacity from 7 GW to 37 GW from 2007-2014, equivalent to a VRE penetration increase from 1% to 5%.

4.2. Energy efficiency

In Fig. 11 the average energy efficiency trends of coal-fired power plants of the three VRE penetration groups are presented. The average coal efficiency of VRE-high was highest at the start of the timeframe due to the modernity of the installed power plants. The average energy efficiency in this year was 38%. During the earlier period in VRE-medium and VRE-low (from 1990 onwards) the energy efficiency increased. In VRE-medium the energy efficiency levelled between 38% and 39% from 2003-2014. In VRE-low this levelling occurred at a lower efficiency between 36% and 37%, but within the same timeframe. The overall lower energy efficiency in VRE-low was mainly caused by low efficiency lignite fuelled power plants in countries like Poland, Slovakia and Czech Republic [34]. This lack of energy efficiency improvement from 2000 onwards can be explained by the trend in average year of commission in Fig. 12. Even though there is an increasing trend in average year of commission, indicating decommissioning of old power plants and/or commissioning of new power plants, the increase was low. In VRE-medium the average year of commission increased only from 1976 in 2000 to 1979 in 2011 and in VRE-low the average year of commission increased from 1976 in 2000 to 1981 in 2011. Since 2010 there appears to be a decreasing trend in the energy efficiency in VRE-high, from 40% to 38%, which is higher and more consistent than previous singular energy efficiency decreases and may be linked to the high FLH decrease of 28%.

In Fig. 13 the trends of gas-fired power plant efficiencies are presented for the three VRE penetration groups. In all three VRE penetration groups the gas-fired efficiency increased from 1990 onwards. The low starting energy efficiency in VRE-high was due to gas-fired capacity only consisting of peaking units. The energy efficiency of VRE-low levelled between 43% and 45%, while the energy efficiency of VRE-medium levelled around 50%. The energy efficiency in these two VRE penetration groups stopped increasing from around 2008 onwards. In Fig. 14 the trends in average year of commission are presented and from this figure it can be identified that the average year of commission in both VRE penetration groups continues to increase from 2008 to 2011. The increase in average year of commission in VRE-medium is 2 year and in VRE-low 5 years. The lack of energy efficiency increase from 2008 onwards may partly reflect increased VRE penetration where gas-fired plants compensate for the intermittency of VRE, but is also linked to the identified decrease in electricity generation from 2008 onwards in the previous section, caused by the financial crisis, causing power plants to shut down or force into part load operation. In VRE-high the energy efficiency reached a maximum of 53% in 2008. However, from 2011 onwards the energy efficiency experienced a decrease til 48–49%. This decrease is higher and more consistent compared to the decreases in 2006 and 2009–2010. It is therefore plausible that in VRE-high the decrease in energy efficiency from

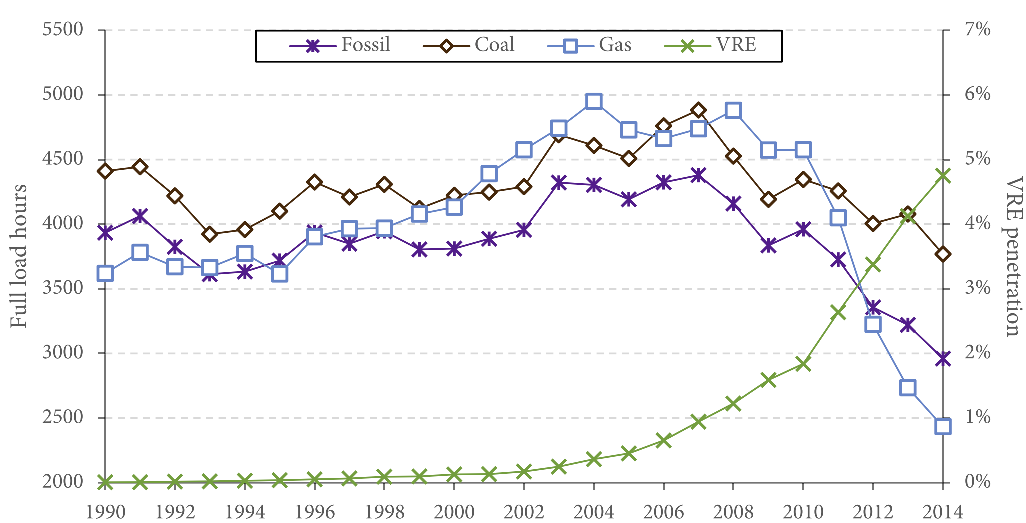

Fig. 9. Full load hours trends and VRE penetration of VRE-low.

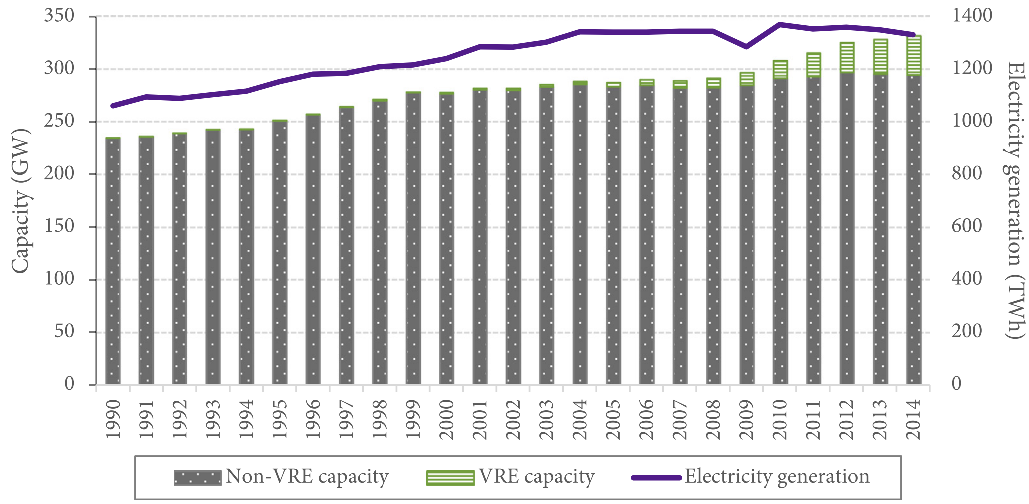

Fig. 10. Electricity generation, non-VRE and VRE capacity trends of VRE-low.

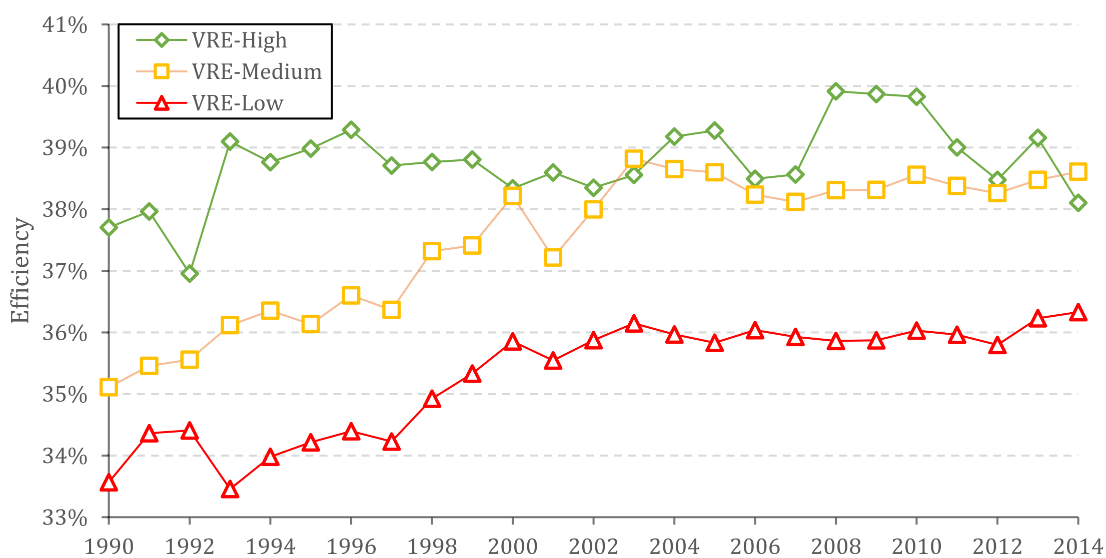

Fig. 11. Average energy efficiency (%) of coal-fired power plants (based on Eurostat [1]).

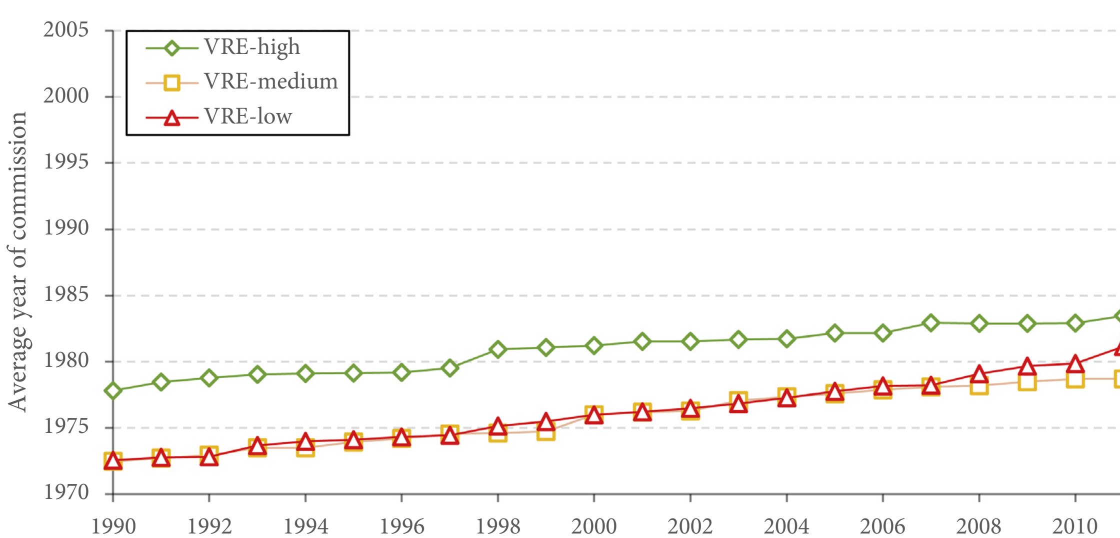

Fig. 12. Average year of commission (year) trends of coal-fired power plants from 1990-2011 (based on Platts [20]).

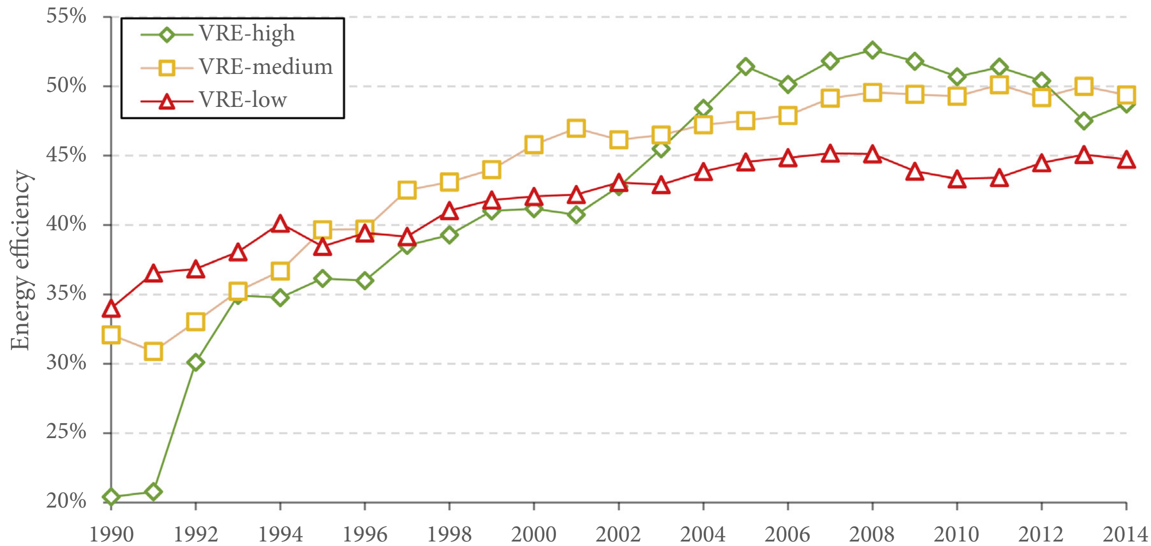

Fig. 13. Average energy efficiency (%) of gas-fired power plants (based on Eurostat [1]).

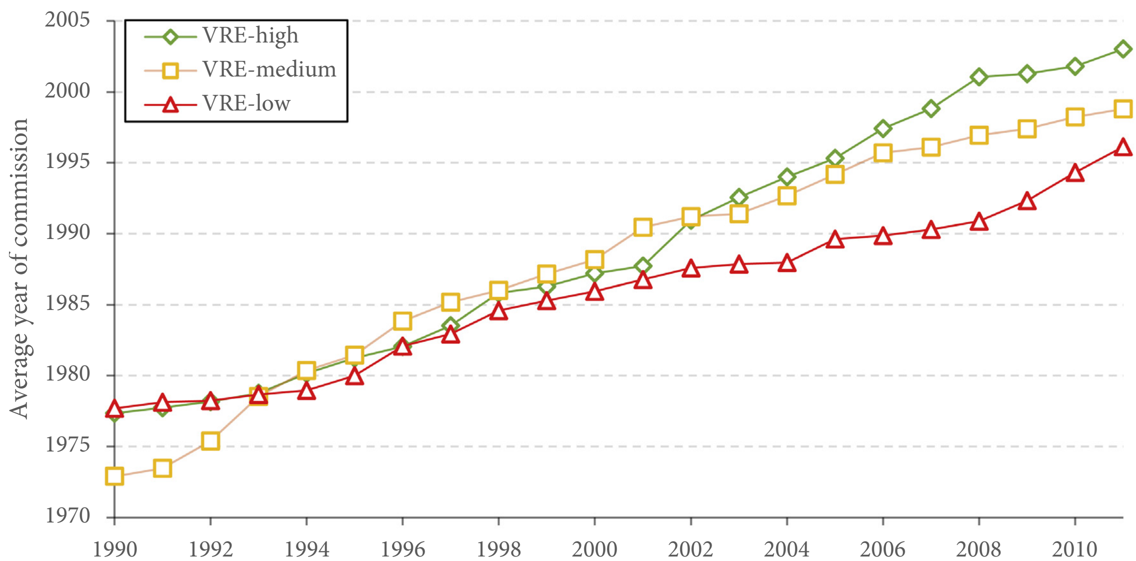

Fig. 14. Average year of commission (year) trends of gas-fired power plants (based on Platts [20]).

51% in 2011 to 49% in 2014 was mainly caused by the decrease of FLH.

The relative share of import + export compared to the total electricity generation is presented in Fig. 15. The hypothesis that in countries with high VRE penetration the share of import + export is highest is rejected by the results. The share of import + export was found to be highest in VRE-low, indicating other factors are of influence, such as electricity prices.

4.3. Correlation and regression analyses

From the full load hours and energy efficiency developments some general trends are visible:

- The increase in natural gas FLH in the nineties (from about 3000s to 5000s FLH) and in energy efficiency in the whole period (from 20-35% in 1990 to 45–50% in 2014), both due to the installation of new capacity.
- The increase of VRE penetration in the 2000s.
- The decrease in FLH for all fossil fuels after 2005 (for VRE-high) and 2007 (for VRE-low and medium). FLHs of natural gas decrease most in the 2010s.
- The impact of the economic recession on electricity demand after 2007.

The trends for VRE, full load hours and energy efficiency are summarized in Table 3.

In order to assess the effect of the recession we calculated a recession indicator (see Table 4, based on formula (4) in section 3.4) which reflects the deviation of the trend for GDP in the period 1990–2006 with the development after 2007. For the years before 2007 this factor therefore is equal to 1. The ratio increases most for VRE-high, reflecting the largest deviation of actual GDP development from the historical trend. This could mean that the impact of the recession on full load hours is biggest for VRE-high. Table 4 also shows the growth rates for electricity demand that show similar

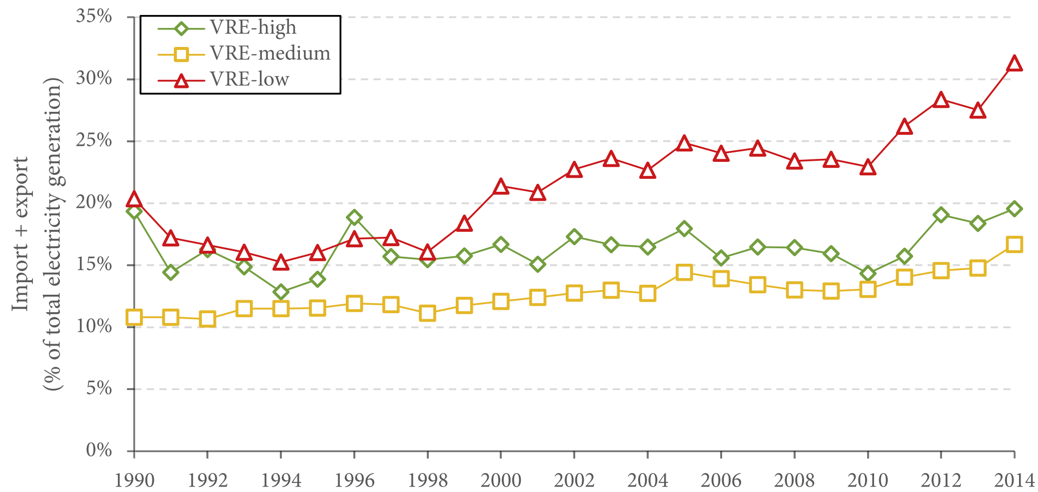

Fig. 15. Relative share of import + export (%) compared to total electricity generation (based on European Commission, 2016).

Table 3
Summary of development VRE, FLH and energy efficiency.

	VRE (%)	VRE (TWh)	FLH Nat. gas	FLH Coal	Energy efficiency Gas (%)	Energy efficiency Coal (%)
Period	*2000–2014*	*2000–2014*	*2000–2014*	*2000–2014*	*2000–2014*	*2000–2014*
VRE-high	3 to 25	9 to 98	4550–1610	6000–4000	42 to 53 to 49	38 to 38
VRE-medium	0.8 to 13	11 to 190	5600–2300	4900–4900	46 to 49	38 to 39
VRE-low	0.1 to 4.8	1.5 to 63	4100–2400	4200–3800	42 to 45	36 to 36

Table 4
Development electricity demand, GDP growth and recession indicator.

	Average growth electricity demand (%/yr)		GDP growth (%/yr)		Recession indicator
Period	1990–2006	2007–2014	1990–2006	2007–2014	2006–2014
VRE-high	3.7	−0.9	3.1	−0.2	1 to 1.30
VRE-medium	1.4	−0.8	1.8	0.4	1 to 1.11
VRE-low	1.6	−0.1	2.4	0.9	1 to 1.12

developments as the GDP growth rates.

In order to assess the impact of VRE on full load hours and energy efficiency we focus the correlation and regression analysis on the period of 2000–2014, where VRE grows most strongly. Table 5 shows the correlation of included factors with FLH and energy efficiency for natural gas and coal per VRE penetration group.

Both the share of VRE and the recession indicator show a strong correlation with full load hours of natural gas for all three

Table 5
r^2 values with full load hours and energy efficiency, for period 2000–2014 (av. com. yr = average commissioning year; nat. gas = natural gas).

r^2 values	FLH - natural gas			FLH - coal		
	VRE-high	VRE-medium	VRE-low	VRE-high	VRE-medium	VRE-low
VRE (%)	**−0.92**	**−0.98**	**−0.89**	**−0.83**	−0.22	**−0.70**
VRE (TWh)	**−0.91**	**−0.98**	**−0.89**	**−0.84**	−0.20	**−0.70**
Electricity demand (TWh)	−0.15	0.06	−0.19	−0.44	*0.56*	0.07
Recession indicator	**−0.98**	**−0.93**	**−0.86**	**−0.75**	−0.49	**−0.81**
Import + export (%)	*−0.53*	**−0.95**	**−0.71**	0.04	−0.39	**−0.80**
Nat. gas price ($\$_{2010}$/GJ)	*−0.52*	*−0.63*	−0.34	**−0.66**	−0.03	−0.15
Coal price ($\$_{2010}$/GJ)	−0.35	−0.43	−0.07	**−0.70**	−0.20	−0.07
Av. com. yr gas/coal	*−0.62*	**−0.88**	−0.18	**−0.78**	**−0.82**	−0.09
r^2 values	Energy efficiency - natural gas			Energy efficiency - coal		
	VRE-high	VRE-medium	VRE-low	VRE-high	VRE-medium	VRE-low
VRE (%)	*0.52*	**0.65**	**0.75**	0.16	0.31	0.24
VRE (TWh)	*0.56*	**0.66**	**0.74**	0.20	0.31	0.24
Av. com. yr gas/coal	**0.90**	**0.88**	−0.08	*0.62*	0.44	0.56
FLH gas/coal	−0.21	*−0.62*	**−0.76**	−0.50	0.12	0.14

Note: Values with p-value below 0.01 are bold and below 0.05 italic.

Table 6
Linear regression analyses for FLH and energy efficiency (for period 2000–2014).

B coefficients (significance)	FLH - natural gas (hours)			FLH – coal (hours)		
	VRE-high	VRE-medium	VRE-low	VRE-high	VRE-medium	VRE-low
Model 1	**(0.00)**	**(0.00)**	**(0.00)**	**(0.00)**	**(0.00)**	**(0.00)**
VRE (%)	15 ± 31 (0.63)	**−215** ± **32 (0.00)**	−343 ± 226 (0.15)	*−195 ± 80 (0.03)*	**110** ± **37 (0.01)**	143 ± 102 (0.19)
Recession indicator	**−11114** ± **2123 (0.00)**	−4970 ± 2625 (0.08)	−4006 ± 7631 (0.61)	5116 ± 5573 (0.38)	**−11623** ± **3110 (0.00)**	*−9989 ± 3468 (0.01)*
Model 2	**(0.00)**	**(0.00)**	(0.06)	**(0.00)**	(0.44)	**(0.00)**
VRE (%)	**−138** ± **16 (0.00)**	**−270** ± **14 (0.00)**	−457 ± 67 (0.00)	**−125** ± **24 (0.00)**	−17 ± 22 (0.44)	**−138** ± **39 (0.00)**
	Energy efficiency - natural gas (pp)			Energy efficiency – coal (pp)		
Model 3	**(0.00)**	**(0.00)**	(0.16)	*(0.03)*	(0.27)	(0.11)
Av. com. yr gas/coal (yr)	**0.8** ± **0.1 (0.00)**	*0.3 ± 0.1 (0.02)*	$7.0*10^{-3}$ ± 1 (0.93)	0.1 ± 0.3 (0.76)	0.2 ± 0.1 (0.13)	0.1 ± 0.04 (0.05)
FLH gas/coal (1000)	**2.4** ± **0.7 (0.01)**	0.15 ± 0.06 (0.81)	1.7 ± 0.8 (0.07)	0.33 ± 0.02 (0.10)	0.29 ± 0.04 (0.42)	0.31 ± 0.03 (0.34)

Note: p-values are given between brackets; values below 0.01 are bold and below 0.05 italic.

penetration groups and for coal only for VRE-high and VRE-low. This is because for VRE-medium FLH for coal remain the same. For electricity demand itself there is little correlation with FLH. This is because electricity demand does increase but much less than before the recession. Therefore the recession indicator reflects better the impact of the recession on FLH.

For energy efficiency, the commissioning year shows a strong correlation for natural gas, reflecting the higher efficiency level for newer capacity. There is limited direct correlation visible for FLH and energy efficiency, likely because of the disturbing impact of capacity age. In the regression analysis we therefore correct for capacity age.

Since we aim to assess the influence of VRE on FLH and FLH on energy efficiency we make separate regression models for both (VRE and FLH, and for FLH and energy efficiency), see Table 6. For VRE and FLH we make two models one with the recession indicator and VRE (%) penetration level included and one with only the VRE (%) penetration level. For FLH and energy efficiency we include average commissioning year and FLH.

The significant models and variables ($p < 0.05$) indicate that the impact of VRE on FLH is −270 to −138 h per percent-point (pp) increase of VRE for natural gas. For coal this range is from −138 to 110 h. The upper value is for VRE-medium where coal-fired full load hours do not decrease in the analysed period. For VRE-high, model 1 gives the recession as significant variable for the decrease in gas-fired FLH and the share of VRE is not significant in this model. This means that the trend of gas-fired FLH for VRE-high could be explained with equal significance by the recession as by the share of VRE (model 2). This is not the case for VRE-medium where the impact of the recession is not a significant variable in model 1, but the share of VRE is significant.

Two models give a significant impact of the recession indicator on full load hours; one for natural gas and one for coal. They predict for a 10% lower GDP than expected a decrease in FLH of about 1100 ± 200–300 h.

For energy efficiency the impact of average commissioning year is 0.3–0.8 pp for natural gas per year and about 2.4 pp impact per 1000 FLH change. For coal the relationships for energy efficiency were not significant.

Combining the regression analyses we find that a 10 pp increase in VRE could lead to a 1400-2700 decrease in FLH of natural gas. This would decrease the efficiency of natural gas-fired power generation by 3.4–6.5 pp. Note that if average capacity age decreases by 10 years the energy efficiency level could still improve since this would increase efficiency by 3-8 pp.

5. Discussion of uncertainties

There are a number of uncertainties present in the statistics used and in the assumptions taken to calculate and compare the full load hours and energy efficiency of fossil-fired power plants in the EU-27. This section provides an overview of the main uncertainties.

5.1. Capacity data and full load hours

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. National statistics were used for the 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 largely consistent with the WEPP database. For some countries deviations were found, mainly for France (+31%) and Italy (+11%). For these countries the percentage change was derived from the national statistics for each year within 2012–2014 and applied to the latest value available in the WEPP database: 2011. If the national statistics of these two highest deviating countries (Italy in VRE-medium and France in VRE-low) would have been used for the period 2012–2014, this would results in a 3% lower fossil full load hours in VRE-medium and 5% lower fossil full load hours in VRE-low for the years 2012, 2013 and 2014. These small percentage decreases would not affect the main results of the study.

A second uncertainty in capacity data arises from mothballing of power plants. This concerns the taking offline of capacity if the electricity demand in a country is significantly lower than the total installed electrical capacity. The least profitable power plants are usually taken offline first. Mothballing is aimed at temporarily shutting down the power plant until the demand for electricity increases again. Systems are put in hibernation and protective measures are taken to make sure equipment is preserved and to prevent damage. This way the power plant's expenditures are cut down and controlled. In the 2010s many fossil-fired power plants in the EU were mothballed. This is in principle reflected in the national statistics used and the WEPP database, but it cannot be determined if all included power plants were actually online. Therefore part of the low load hours may be explained by offline capacity. Offline capacity can have an impact on the energy efficiency. The degree of part-load operation and increased start-ups/shutdowns would be lower than expected from the full load hour results (increasing the efficiency). On the other hand many (new) NGCC power plants were mothballed with high energy-efficiencies which could have a downward effect on the energy efficiency.

The power plants in Platts [20] 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

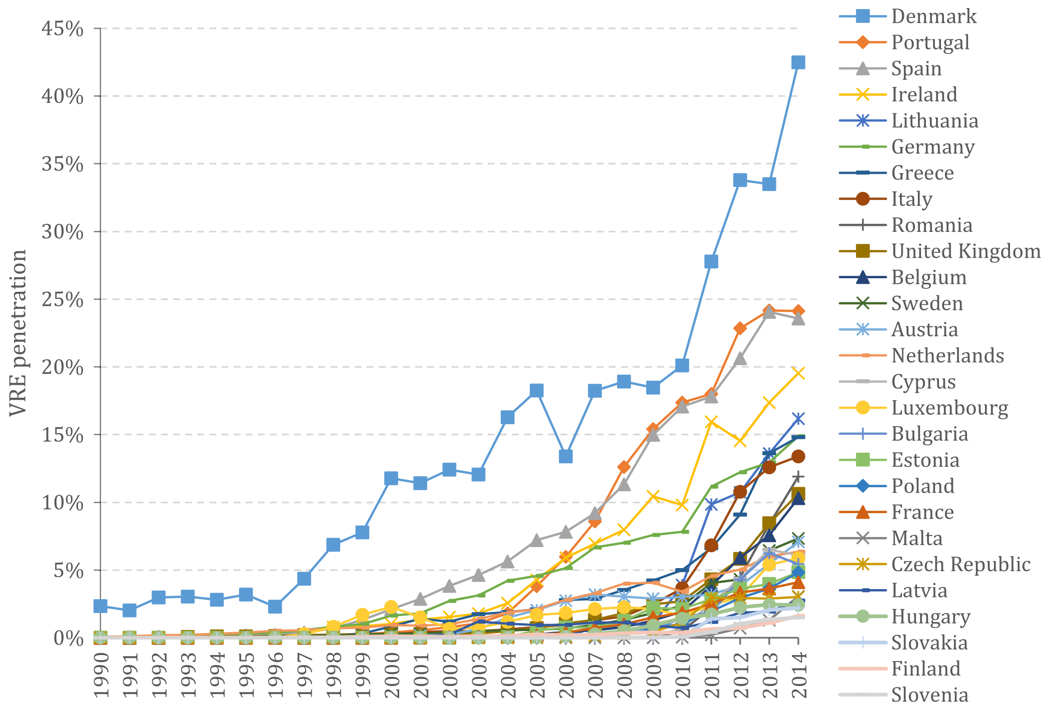

Fig. 16. Development of VRE penetration per EU member state.

the biomass is not categorised under a type of coal but under biomass, while the capacity is categorized under coal. This will have a decreasing effect on the full load hours of the coal-fired power plant, even though the power plant is not losing operating time. To provide an indication of the maximum possible effect, it can be calculated what the effect would be if all electricity produced from biomass would have been produced in coal-fired power plants. If in 2014 (where the biomass production is highest from 1990-2014) all electricity produced from biomass was generated in coal-fired power plants, the average full load hours of coal-fired power plants in the EU-27 would need to be corrected 10% upwards.

5.2. *Energy statistics*

In contrast to the full load hour calculations, where autoproducers were included as the WEPP database did not make a distinction between main activity and autoproducer plants, in the energy efficiency calculations autoproducers were excluded. This decision was made based on the assumption that autoproducers typically do not adjust their production depending on VRE output like main activity power plants do. However, since no other option was available, in calculating full load hours autoproducers were included. In 2014, 4.8% of the electricity produced from coal, gas and oil was produced by autoproducers. It is difficult to determine whether the full load hours of the average autoproducer are higher or lower than the average public power plant. However, it is likely that the full load hours of autoproducers remained more constant in the most recent years compared to the decreasing trend found in total fossil full load hours in all three VRE penetration groups, since industrial processes require a more constant electricity flow. Therefore it may be that the decrease in fossil full load hours would be slightly (due to only 4.8% of total electricity being produced by autoproducers) higher if autoproducers were excluded from the calculations.

Uncertainties in energy efficiency calculations arise from the input data from Eurostat statistics regarding electricity generation, heat output and fuel input. Especially for smaller countries or fuels the uncertainty is greater. The advantage of using Eurostat statistics (which are consistent with IEA statistics) is that they present country statistics in a harmonized way (e.g. all power generation is given as gross power generation, the fuel input is based on net calorific value and CHP plants are included by the same statistical method). No other data sources that provide information in this manner are available.

5.3. *Aggregating EU member states into VRE penetration groups*

The EU member states were divided into three VRE penetration groups based on the VRE penetration in 2014. However, the VRE penetration groups were analysed from 1990-2014. During the timeframe of 1990–2014 the development of VRE penetration differed for each member state. In Fig. 16 the development in each EU member state is presented. As can be identified from the figure, Germany for example was the country with the third highest VRE penetration from 2001-2005. But due to the lower growth after this period compared to Portugal and Ireland, Germany is allocated to the medium VRE penetration group. The decision was made to aggregate static, based on one year, as switching countries between 1990 and 2014 based on VRE penetration would cause high deviations in full load hour and energy efficiency trends in years where countries were switched. These high deviations would be caused by, for example, the different types of coal-fired power plants in each country which have unequal energy-efficiencies.

The method used for aggregating countries into VRE penetration groups was based on weighted averages instead of considering each country equal and taking the average full load hours/energy efficiency of all member countries within a VRE penetration group. This decision was made to maintain large countries having a higher impact on the results within a VRE penetration group, as smaller countries may compensate VRE output more easily with import and export.

6. Conclusion

This study aimed at determining whether the implementation of VRE had an effect on full load hours and energy efficiency of fossil-fired power plants in the European Union from 1990-2014. For this purpose we analysed the VRE penetration of each EU member state and aggregated the member states into three groups with different VRE penetration levels in 2014 (VRE-high 15%+, VRE-medium 7.5%–15% and VRE-low 0%–7.5%). These VRE penetration groups were then analysed based on full load hours and energy efficiency and compared to each other.

In all three groups the fossil full load hours were found to be decreasing in the most recent period from 2005/2007–2014. The largest decrease was found in the penetration group with the highest VRE penetration: VRE-high (53% from 2005 to 2014), followed by VRE-medium (34% from 2007 to 2014) and lastly VRE-low (33% from 2007-2014). In absolute numbers the decrease in full load hours found in this study were up to 3000 h for natural gas and 2000 h for coal. This is higher than the values in literature, where the biggest decrease for similar increasing VRE penetration levels were 988 h (−15%), 483 h (−8%) and 346 h (−5%) fossil full load hours.

Both the share of VRE and the recession indicator show a strong correlation with full load hours of natural gas and coal. A linear regression analysis gives indications for the impacts of the share of variable renewable electricity generation on the average full load hours of fossil-fired power plants, which are up to −270 to −125 h per pp increase of VRE. These values are uncertain though since overcapacity (related to the financial crisis) is a factor that is difficult to estimate. The regression analysis shows that for VRE-high this factor can be equally significant in predicting the developments for natural gas. A 10% lower GDP than expected could reduce average full load hours by about 1100 h. For VRE medium no significant relation with the recession was found but only with the share of VRE and for VRE-low both factors were not significant.

For energy efficiency, the commissioning year shows a strong correlation for natural gas. A linear regression analysis gives an impact per average commissioning year of 0.3–0.8 pp energy efficiency improvement. For full load hours the impact is about 2.4 pp per 1000 h. For coal the relationships for energy efficiency were not significant. The value for natural gas is within the values found in literature where the effect of increased start-ups on coal- and gas-fired power plants, amounted to up to 0.3 pp and 0.5 pp, respectively. For part-load operation a decrease of up to roughly 10 pp for coal-fired power plants and 20 pp for gas-fired power plants, was found.

Nomenclature and abbreviations

av. com. yr	average commissioning year
C	Installed capacity (MW)
Commissioning year	Year power plant went into operation
CCGT	Combined cycle gas turbine
CHP	Combined heat and power plant
E	Gross electricity output from public power and CHP plants (TWh)
EU	European Union
Energy efficiency	Year-round average energy conversion efficiency (%) of electricity generation
FLH	Full load hours (hours per year)
GDP	Gross Domestic Product
GT	Gas turbine
h	hour
H	Heat output from public CHP plants
I	Fuel input in lower heating value
IGCC	Integrated gasification combined cycle
nat. gas	natural gas
n/a	not available
PCC	Pulverized coal combustion
Penetration of VRE	Share of variable renewable electricity in electricity generation (%)
pp	percent point
PV	Photovoltaics
RST	Retrofit steam turbine
s	Correction factor between useful heat and electricity (power loss factor)
SCGT	Simple cycle gas turbine
SRMC	Short-run marginal costs
ST	Steam turbine
STh	Solar Thermal
Tot	Total
VRE	Variable renewable electricity (TWh)
VRE-high	Group of countries with VRE penetration level of 15% or more
VRE-medium	Group of countries with VRE penetration level between 7.5% and 15%
VRE-low	Group of countries with VRE penetration level between 0% and 7.5%
W	Wind
yr	year

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