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Title: Challenges in load balance due to renewable energy sources penetration: the possible role of energy storage technologies relative to the Italian case

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Abstract: With the rapid growth of the electricity produced by renewable energy sources (RES), especially those highly variable and unprogrammable (e.g. wind and solar power), the need of energy system flexibility increases significantly.

Since RES currently represent a significant fraction of the power supply, their variable nature poses challenges to power grid operation, such as RES curtail and loss in global efficiency of thermoelectric plants, since they are often operated at part-load as fluctuating back-up power.

In particular, thermoelectric plants recently moved their role from base-load power to fluctuating back-up power. Such a cycling operation represents a less obvious effect of grid flexibility requirement due to RES penetration. Main effect is the increment of both energetic costs, due to reduced efficiency operation, and wear-and-tear costs.

This aspect is deeply analyzed in reference to the Italian electricity generation mix in the period 2008-2012. Moreover, the possible coupling of energy storage systems with thermoelectric plants is highlighted as an alternative solution respect to retrofitting of existing plants.

The recent liberalization of the electricity markets, together with the rapid expansion of the utilization of RES (renewable energy sources), has emphasized the problem of the electrical grid imbalance. In particular, due to highly variable and unprogrammable RES behaviour, the need of energy system flexibility increases significantly.

In the Italian scenario, actually, RES represent a significant fraction of the power supply but due to their variable nature, natural gas combined cycle plants (CC) in the period from 2008 to 2012 were managed to compensate the RES growth and, therefore, partly operated with negative effects in terms of global efficiency.

The changed role of CC plants, or rather from base-load power to fluctuating back-up power, has introduced the problem of cycling operation that represents a less obvious effect of grid flexibility requirement due to RES penetration. Main effect is the increment of both energetic costs, due to reduced efficiency operation, and wear-and-tear costs.

In this paper, this aspect is analysed in reference to the Italian electricity generation mix in the period 2008-2012, specially focus on the possible role of energy storage systems as possible solution to overcome grid unbalance, plant efficiency penalty and the increase of O&M costs.

***Point-to-Point Response to Reviewers**

*Dear Reviewers and Editor,*
*I would like to sincerely thank the reviewers for their comments and the appreciation shown for our paper.*
*In the following, all reviewers' comments are in blue, and our answers are in light blue (italic).*
*Best Regards*

Ms. Ref. No.: EGY-D-15-00547R1

Title: Challenges in load balance due to renewable energy sources penetration: the possible role of energy storage technologies relative to the Italian case

**Reviewers' comments:**

**Reviewer #1:** According to the answers given to my first review, and taking into account that the energy analysis model is yet quite simple and some effects could not be included in the study, I consider that the paper could be published as it is corrected now. Anyway, I suggest to include a section entitled "discussion" (before "conclusions"), in which model assumptions and limitations are presented, in order to check the certainty of the results obtained by this energy policy study.

*Thanks for your comments and the appreciation shown. Authors consider that adding an extra section called "discussion" could weigh down the already complex manuscript and it could lose clarity.*

**Reviewer #2:** I do not have additional questions or comments. I consider a very interesting discussion and adequate to Energy scope.

*Thanks for the appreciation shown.*

**Reviewer #3:** According the the revised version of the paper, I can say that a good work has been done and the manuscript has been considerably improved. Hoverer there are still some minor correction that should be applied.

*First of all, thanks for the appreciation shown.*

1. The Authors keep using "electric production" phrase within the entire manuscript. I suggest to convert it into: "electricity production".

*The suggested conversion was carried out.*

2. In section 2.2 Performance analysis of single technologies, it states:
"For each plant typology, the equivalent operating hours were calculated by the ratio of gross production (Pg) and gross installed power (Wg), both relative to the same year (Eq.1)."

In my opinion, since there is a Nomenclature section in the paper, there is no need to explain equation's parameters in the text. I suggest shortening equivalent operating hours description to: "For each plant typology, the equivalent operating hours were calculated according to the Equation 1:". At the same time, move Pg and Wg description to the Nomeclature section.

*The Nomenclature section and the indicated sentence was updated as suggested.*

3. Section 3.3 ESS-CC solution: quantitative analysis.
There is the discussion on EES penetration effect on storage energy Est, where Authors explain:
„In order to guarantee the Pcc data indicated above with a CC plants efficiency of 54.6%, the proposed operation strategy implies the shutoff of 43.8% thermoelectric plants, in terms of current capacity. In particular, the ESS penetration, in the measure indicated above, allows to have 14,280 MW working for 3,547 Heq under 54.6% efficiency, instead of 9,996 MW with an operation time of 5,067 Heq calculated without ESS. In fact, 30% of stored energy (Est) with respect to Pcc_2012 is determined as (Eq.3):"

Why the value of Heq, expressed in hours (see Nomenclature section), is presented as: 3,537 Heq. In my opinion, it is better to continue the discussion using for instance ....14,280 MW working for 3,547 hours of Heq. Apply the same change within the entire manuscript, whenever giving Heq value.

*The term was left as it is, because the authors consider that the numerical values referring to* $H_{eq}$ *(e.g. 3,547) are directly equivalent hours.*

I suggest to accept the manuscript for the publication if the Authors apply minor corrections.

**Reviewer #4:** Most of my comments have been considered in the revised version of article. For the few remains, as author mentioned, data are not available which will not damage the meaningfulness of the article. Therefore the changes in the revised article were satisfied me and I have no more comments. I suggest accepting of this article as it is an important and interesting topic.

*Thanks for the appreciation shown.*

Comments from the Editor

Some additional issues to be dealt with:

Would you clearly mark all improvements/correction in the manuscript by using TRACK CHANGES or by coloured font/background?

*All improvements were marked in a separate file.*

# Highlights

- Impact of renewable sources on the Italian thermoelectric sector
- Renewable energy sources growth leads to energy system flexibility
- Thermoelectric plants used as back-up power leads to 6.3% energy penalty
- Energy storage systems (ESS) permit an energy saving about 100 M€/year
- ESS adoption mitigate wear-and-tear costs of about 18.5 to 50.2 M€/year

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## Abstract

With the rapid growth of the electricity produced by renewable energy sources (RES), especially those highly variable and unprogrammable (e.g. wind and solar power), the need of energy system flexibility increases significantly.

Since RES currently represent a significant fraction of the power supply, their variable nature poses challenges to power grid operation, such as RES curtail and loss in global efficiency of thermoelectric plants, since they are often operated at part-load as fluctuating back-up power.

In particular, thermoelectric plants recently moved their role from base-load power to fluctuating back-up power. Such a cycling operation represents a less obvious effect of grid flexibility requirement due to RES penetration. Main effect is the increment of both energetic costs, due to reduced efficiency operation, and wear-and-tear costs.

This aspect is deeply analyzed in reference to the Italian electricity generation mix in the period 2008-2012. Moreover, the possible coupling of energy storage systems with thermoelectric plants is highlighted as an alternative solution respect to retrofitting of existing plants.

# Keywords

Plant flexibility; plant cycling; energy storage; grid imbalance

# Nomenclature

| | | |
|---|---|---|
| $E_{st}$ | energy stored | (MWh) |
| $H_{eq}$ | equivalent operating hours | (h) |
| $M_{dp}$ | mean delivered power | (MW) |
| $P_{CC}$ | electricity production | (GWh) |
| $P_{CC\_2012}$ | electricity production of 2012 | (GWh) |
| $P_g$ | gross electricity production | (GWh) |
| $W_g$ | gross installed power | (GW) |

# 1 Introduction

In the next years, a rapid growth of renewable sources exploitation is foreseen in order to cover with renewable sources up to 20% of the final energy consumption in 2020 and an even larger share by 2050 [1]. In fact, RES technologies are expected to take the leadership in the forthcoming energy generation portfolio in order to achieve a sustainable energy generation. Anyway, their utilization is slowed down by the characteristic intermittency and the fluctuating trend and, moreover, by the inadequacy of electricity networks. To ensure such a penetration, electricity systems need to be flexible in order to balance at every moment generation and consumption.

In some European countries (Denmark, Spain and Germany) the renewable energy share has already exceeded 20% [2], highlighting critical issues such as grid congestion and perturbation [3],[4] due to the large number of highly unpredictable, intermittent and fluctuating power plants [5]. Moreover, in order to mitigate the serious concerns indicated above, RES are curtailed during low consumption periods limiting the exploitation of renewable power plants.

What above represents the critical issues, relative to the RES exploitation, usually analysed in literature [6]-[10] together with the possible solution identified in energy storage systems (ESS) integration, mainly contributing to:

- grid reliability improvements thanks to the reduction in both fluctuating energy delivered to the grid and energy absorption from the grid (leading to mitigation of grid overload);
- reduction in curtailment of unprogrammable renewable energy generation due to network constraints;
- deferring investments of grid improvement.

A further negative aspect to overcome is the RES impact on thermoelectric power generation. In literature, few articles deal with RES implications on conventional power generation; however, some specific studies on wind variability and its effect on traditional generators are available. A model to estimate emissions from fossil fuel generators used to compensate variable wind and solar power is presented in [11]. Specifically, a quantification of $CO_2$ and NOx emission is provided considering natural gas turbine as power technology used to compensate variable renewables. An interesting model of wind/gas/energy storage generation systems, described in [12], demonstrates a method for integrating significant quantities of wind energy while reducing power fluctuations, showing the financial feasibility of the solution in relation to the produced wind energy.

In the present paper, the particular issue of RES impact on conventional power generation is analysed with particular attention to the Italian scenario. As detailed in the following, in order to overcome the grid balance problem due to the difference between energy generation and consumption, part of the Italian thermoelectric plants were managed in the last years as backup of RES. The consequent significant negative effects on thermoelectric generation performance are deeply investigated in this work. In fact thermoelectric plants, with particular reference to combined cycles (CC), are operated as part-loaded plants, which can be ordered to increase or decrease output as required, and generally subjected to hot and cold stand-by periods. This cycling operation causes a significant reduction in electric efficiency (CC plants exhibit the greatest efficiency degradation when operated in part-load conditions [13],[14]) and thermal/pressure stresses resulting in a relevant wear-and-tear damage [15],[16]. These aspects bring about an increasing of fuel costs and O&M costs due especially to more frequent repairs, reduced component life and more frequent forced outages [15]-[18].

Therefore the cycling aspect, or rather the power output variation due to starting up, shutting down, ramping up and down [17], is a central issue consequent to the increasing penetration of RES in the electricity generation system [19].

During power plant cycling, as anticipated, components suffer of large temperature and pressure stresses than lead to accelerated component failures and forced outages [18]. Consequently, costs associated with power plant cycling, widely studied in literature [17],[20],[21], are due to five significant components [20]: capital replacement costs and maintenance cost, cost of forced outages due to cycling, capital replacement costs and maintenance cost related to load following, cost for fuel, $CO_2$ emissions and auxiliary services during start-up, beyond that cost for decrease in rated efficiency.

For what above the research of solutions that can mitigate problems caused by cycling became crucial. To this regard, preclusions relate to any solution that requires the construction of new power plants, due to the already too large installed power and further curtailment of RES. Therefore, the most plausible solutions are identified to act directly on the existing power generation facilities. A potential approach is, in fact, the retrofitting of existing power plant [22]. Recent improvements [23] regard the operation flexibility enhancement (i.e. faster re-start and ramp faster within a wider load range) and, preliminarily, solutions to increase efficiency at part load and mitigate thermal and pressure modulation varying load condition [24].

Therefore, in this paper an alternative solution is proposed and preliminarily analysed. In particular, the energy storage systems (ESS) integration with large thermoelectric plants (specifically combined cycles) is proposed. This solution could allow operation in conditions closer to the nominal ones, obviously reducing cycling and consequent penalties indicated above. In other words, the energy surplus generated by CC plants, that can work close to nominal conditions, can be stored by ESS avoiding their continuous shutdown and restart.

At system level, no previous studies are available regarding the analysis and quantification of efficiency penalization on the thermoelectric sector due to RES penetration. In the research work herein presented, CC plants part-load operation, as RES backup, and related efficiency are evaluated by using quantitative parameters. In particular, the analysis is carried starting from the analysis of operation data of the whole Italian thermoelectric power generation sector with reference to the period 2008-2012 (Section 2), by analyzing performance of single plant technologies (Section 3). Consequently, the impact of RES exploitation on the thermoelectric generation efficiency is evaluated, relative to the Italian case, in terms of primary energy penalty. Basing on these results, a reference management strategy of CC plants is identified (Section 4); moreover the impact of their possible coupling with ESS is quantified limited to the advantages related to fuel and wear-and-tear costs.

# 2 Material and data analysis

## 2.1 Analysis of production and fuel consumption of the whole thermoelectric power generation sector

In this section data relative to installed power and energy production of systems connected to the Italian grid are described and analyzed. The source is the annual reporting of Terna, the Italian energy Transmission System Operator (TSO). Specifically, reports relative to the years from 2008 to 2012 were considered. In this period, the number of unprogrammable renewable power plants increased considerably.

To this purpose, Figure 1 shows the trend of the installed power in the period from 2008 up to 2012. As it can be seen, against a general invariance of thermoelectric and hydroelectric installed power and against a slight gain in the wind energy exploitation, there is a significant increase in photovoltaic (PV) power installations, which grows from 430 MW in 2008 up to 16,420 MW in 2012. Cause of this trend can be related to the important policy mechanism, introduced by Italian Government in February 2007 [25]-[28], designed to accelerate investment in PV technology with a feed-in premium. This incentive campaign ended in July 2013 (for new installations) with the simultaneous depletion of state funds allocated to incentivize those power plants.

**Figure 1 Installed net power in Italy: 2008-2012**

Within the thermoelectric sector, as highlighted in Figure 2, combined cycle (CC) technology has the leading role with a higher than 45% share of the installed capacity in the years 2011-12. Moreover, it can be noted that the installed capacity of condensing steam turbine plants (CST) dropped by 5%, from 2008 to 2012, whereas the installed capacity of repowered power plants (RP), gas turbines (GT) and internal combustion engines (ICE) was left unchanged.

Even with such a sharp decline in installed capacity CST power plants are still the second power generation technology in Italy.

**Figure 2 Percentage of gross installed capacity of each plant technology**

In order to further analyse the evolution of the thermoelectric sector in the observed period, data about production, consumption and efficiency are provided hereinafter. Figure 3 and Figure 4 show, respectively, gross and net produced electric energy for each kind of fuel used in thermoelectric plants. For clarity, gross production is the amount of electricity produced, measured at the terminals of electric generators. Instead net production is the amount of electricity produced, measured at the border of power plants, i.e. deducting the amount of electricity necessary for auxiliary services. From these two figures, it is clear how the use of natural gas is far larger than all other fuels. In particular, considering that the amount of energy produced by natural gas is 4 times as large as that produced by solid fuels, it is easy to conclude how Italian energy production is strongly dependent on natural gas supplies. This is also clear considering the energy consumption data distinguished by fuel type as shown in Figure 5.

**Figure 3 Gross produced electric power from thermoelectric plants in Italy: 2008-2012**

**Figure 4 Net produced electric power from thermoelectric plants in Italy: 2008-2012**

**Figure 5 Consumed fuel for thermoelectric plants typology in Italy: 2008-2012**

However, it is important to emphasize that from 2008 to 2012, there was a noticeable drop in natural gas consumption, mainly due to the reduction in the use of this kind of plants (principally combined cycles fed by natural gas) with a consequent decline in their production. In fact, it can be considered that the decrease in petroleum products was compensated by the increase of solid fuels utilization, which is the logical consequence of the conversion of most oil fuelled thermoelectric plants to coal. This trend was also accelerated by the fall of coal price occurred in 2012 (Figure 6).

**Figure 6 International prices of major energy commodities 2008 – 2012 [26]**

In consideration of what described above and due to the higher price of natural gas, in the period 2008-2012 CC plants were mainly operated to compensate the RES growth occurred in the same period, with a relevant decrease in their annual operating hours, as discussed in the following. The effect of the RES growth influences substantially natural gas CC since:

- from a technological point of view, CC are characterized by a greater flexibility if compared to steam plants fed by solid fuels,
- although CC plants are characterized by greater energy efficiency, they are penalized, as said above, by a higher cost of generation due to the high natural gas cost.

Moreover, analysing the global production and the consumption data, it is also clear how the mode of operation of those plants was changed from base-load to the current mode as fluctuating back-up power. The main effect, always with reference to the period 2008-2012, can be found in the electric efficiency trend of CC plants fed by natural gas. In fact, as discussed in Section 3, a significant decrease in their efficiency can be justified, at first glance, by their sub-optimal functioning. In general, CC plants operating time decreased, with power output increasingly far away the nominal one. In Section 3 the issues relating to CC management are discussed, with reference to the period of analysis indicated above.

It is clear, therefore, that the management strategy of combined cycle produces a significant efficiency penalty with effects on the whole thermoelectric sector, with the exception of combined heat and power plants (CHP), as shown in Figure 7.

**Figure 7 Thermoelectric plants efficiency without CHP in Italy: 2008-2012**

In fact, referring to Figure 7, relative to thermoelectric plants with only electricity production, gross and net efficiency decline of about 0.8 and 1.1%, respectively, from 2011 to 2012. This decline is more pronounced considering the five years under analysis; indeed gross and net efficiency moves from 43.6% and 41.4% in 2008 to 42.3% and 39.7% in 2012. It is interesting to emphasize as this decline corresponds to an increase in the difference between gross and net efficiency, which in 2012 reached the maximum value (with respect to the period of analysis) of 2.6%, suggesting an increasing incidence of auxiliary services on the energy production. This feature, which will be analysed in detail below, is indicative of a growth of part-load operation of power plants.

To prove the negative effect of CC plants management on the global thermoelectric efficiency, it can be noted, with reference to Figure 8, that, if we include CHP plants, the overall decline in thermoelectric performance is lower. Namely, a gross and net efficiency of the overall thermoelectric sector of 46.5% and 44.5% and of 46.2% and 44.0% was measured in 2008 and 2012, respectively.

In fact, with respect to the fluctuating back-up power operation which is now common in CC plants without heat production, CHP plants are characterized by a more continuous operation normally much closer to nominal conditions. This is consistent with their operation in heat tracking mode, not following changes in the power demand from the grid.

**Figure 8 Thermoelectric plants efficiency with CHP in Italy: 2008-2012**

## 2.2 Performance analysis of single technologies

Aiming at further analysing the performance of the thermoelectric sector, it is useful to investigate the actual energy production and the efficiency trends of each energy conversion technology. Also in this case, the source is the annual reporting of Terna, with particular reference to the years from 2008 to 2012.

Starting from the analysis of the gross and net production data, shown in Table 1, it is quite evident that CC technology, or rather the one that guarantees the highest annual production, has produced 40% less energy in 2012 than in 2008, operating far from its nominal power potential. This downward trend is crucial to understand the global plant performance. As it can be seen in Figure 9 andFigure 10, the efficiency of combined cycles is far from typical values of this technology. In particular CC plants, from 2008 to 2012, have lost 1.6 and 1.8% of the gross and net efficiency, reaching values of 52.7% and 51.1%. Moreover, still for CC systems, the gap between the gross and net efficiency values gets larger in the years when the energy production is decreased due to the larger weight of fixed plant energy consumption (i.e. auxiliary service).

**Table 1 Energy production for each power plant technology**

Furthermore, in Figure 9 and Figure 10 it is not possible to identify a common efficiency trend for the different plant technologies. In general, compared to a slight efficiency increase in internal combustion engines (ICE) and condensing steam turbine (CST) plants, a considerable efficiency decrease in gas turbine (GT) and an efficiency drop of re-powered plants (RP) and combined cycles (CC) is observable. It is remarkable that GT, RP and CC plants cover about 60% (over 45% by CC technology) of the total installed thermoelectric power in Italy. Consequently, the global thermoelectric efficiency has decreased in the studied period, as highlighted in previous Section 2 (Figure 7).

**Figure 9 Plants gross efficiency sorted by technology in Italy: 2008-2012**

**Figure 10 Plants net efficiency sorted by technology in Italy: 2008-2012**

As mentioned above, the increased number of hours of part-load operation of these facilities (in particular CC plants) with consequent performance drop, is undoubtedly related to the increase of RES power generation.

Thanks to the campaign of state incentives, mentioned at Section 2, the energy introduced into the grid provided by PV system is increased from almost zero in 2008 to about 19,000 GWh in 2012 (Figure 11). This situation should not be considered isolated from the rest of Europe. For example in Spain, due to the aggressive incentive campaign, the PV production has moved from a 490 GWh in 2007 to about 8,500 GWh in 2012 [4].

**Figure 11 Gross produced electric power for RES in Italy: 2008-2012**

Relative to the Italian case, this increase, along with the simultaneous growth of the produced energy by wind generators (about 10,000 GWh in the period of study), is comparable with the decreased production from CC plants. As further proof of this fact, it is also interesting to analyze the equivalent operating hours ($H_{eq}$) of both thermoelectric power plants (Figure 12) and renewable power plants (Figure 13), with particular reference to wind and PV plants.

**Figure 12 Thermoelectric plants: equivalent operating hours**

**Figure 13 Wind power and PV equivalent operating hours**

For each plant typology, the equivalent operating hours were calculated according to Eq.1.

$$H_{2eq} = \frac{P_g}{W_g} \tag{1}$$

In terms of operating hours, it is possible to observe from 2008 to 2012 a continuous decrease of the use of CCs and a similar increase of photovoltaic and wind energy. The reduction of CC energy production is mainly due to the RES priority of power dispatch to the grid. This means that, in response to a possible decrease in the power demand from grid, the thermoelectric generation has to lower its power output instead of excluding RES production. In particular, the trends depicted in Figure 13, since they represent the ratio between energy production and installed power (Eq.1), correspond to a progressive reduction of wind and PV plants curtailment. This is only possible by switching the operation of CC power plants from base-load to fluctuating back-up power.

In particular, as detailed in Table 2, in the period of study CC equivalent operating hours are halved (from about 4,000 in 2008 to about 2,000 in 2012). The reduction in the operation of RP plants, which were almost totally stopped in the last years, is also significant. The effects of this management strategy must be analyzed also considering the importance of CC and RP plants (about 55% of the installed power in Italy), on the Italian thermoelectric sector (not including CHP plants).

On the other hand, the operation of CST plants is almost unchanged as shown in Figure 10, even though their efficiency is 20 percent points lower than that of CC power plants. This strategy, which implies important energy penalties, was motivated by the lower price of coal, progressively more used in the investigated period consequently to the conversion of the main oil thermoelectric plants.

**Table 2 $H_{eq}$ calculated on the basis of gross production and installed power data**

The reduction in $H_{eq}$ for CC plants is characteristic of their actual use in low load conditions or even shutdown. These operating conditions are far from the optimum operating point, leading, as mentioned above, to a significant efficiency drop. Consequently, it can be asserted that it is necessary to review the utilization of thermoelectric plants in this current scenario strongly influenced by RES. In particular, a strategy, based on ESS coupling to CC plants, is presented in Section 4 to guarantee the CC operation as possible at nominal and steady load.

# 3 Results and discussion

## 3.1 ESS-CC solutions: background & approach

As seen in the previous section, government policies to encourage the diffusion of RES technology (mainly PV), not accompanied by a plan for the electricity grid improvement (including widespread use of ESS) and economic choices, pushing for the use of lower quality fuels (i.e. coal) has led to a substantial decrease of the energy performance of Italian thermoelectric power plants. This is caused mainly by a reduction in operation natural gas plants, such as CC (characterized by the highest efficiency) and their management as fluctuating back-up power to compensate RES production trend, therefore under conditions far away from the optimal ones. Moreover, the energy free market has opened the production of energy to a number of plant operators, who have their own strategies and maintenance scheduling, and a national planning to promote the highest efficiency of the electricity mix seems to be no longer possible.

The current Italian RES capacity, including hydro, geothermal, biomass, wind and solar energy can theoretically satisfy the peak demand without any additional thermoelectric power. Due to the capacity factors of unprogrammable RES, this is not possible, but since a large share of CHP is now in operation, the need for power plants dedicated to electric energy production is now much smaller than in the past.

Any additional RES capacity could clash with the operation of CHP power plants, and reduce the other thermoelectric power plants to a minimal share of energy production. The Italian electricity mix would then be completely rearranged in a way that was totally unexpected just a few years ago. There is therefore a strong need of systems that allow storing energy or improve the energy management and utilization during the days and the year.

Therefore, an important topic can be identified in the development of energy storage technologies, pointing on the strategy of integrating storage technology with the operation of thermoelectric plants and, specifically, reviewing the CC operating conditions. This strategy, in addition to the development of fossil power plants characterized by higher flexibility and sufficiently high efficiency in a wide range of part-load operation, could positively contribute to the efficiency improvement of the entire thermoelectric sector, allowing CC plants operation at nominal conditions and postponing the utilization of the produced energy to follow the demand. To this purpose, an overview of ESS technology and the scenario of ESS integration with CC plants were hereinafter shown.

ESS technologies can be classified in four categories: mechanical, electrical, thermal and chemical. Each category offers different opportunities, but also features some disadvantages.
A further distinction must be made between technologies for "power" applications (delivery of electricity for short periods) and those for "energy" applications (delivery electricity for medium and long periods). As an example, flywheel, supercapacitors and superconducting magnetic energy storage (SMES) are power technologies, while batteries (mainly Na/S and redox batteries as mature and first stage technology respectively), compressed air energy storage (CAES) and pumped-storage hydroelectricity (PSH) are energy technologies.
Even if a large number of technologies are well known or already under development, only a very limited storage capacity is integrated in the European scenario, assessed at around 5% of total installed capacity [2]. Moreover, specifically for "energy" applications, ESS technologies different from Pumped Hydro energy Storage (PSH) (i.e. sodium–sulphur batteries, compressed air energy storage, thermal energy) are minimally integrated. However CAES and some kind of batteries are characterized by a mature level. In the following, some details are provided about ESS technologies for "energy" applications, i.e. CAES and PSH, among mechanical technologies, and batteries.

CAES technology is based on the use of the excess energy to compress air into underground caverns or storage tanks. During discharge, the compressed air expands in a turbine, after the passage through a possible combustion chamber (where natural gas is burned) or a heat recovery system (AA-CAES, efficiency of about 70%) [5], [29]. Considering CAES installation cost and its moderate energy density [30], it is currently suitable only at large scale (>100 MW). Expected improvements, as indicated in [31], are CAES downscale to the MW order of magnitude allowing  the "any site" location (compressed air can be stored in fabricated high-pressure tanks, making ESS location independent of geology) and the development of new simplified high-pressure air turbines with high efficiency, specifically designed for this application.

PSH and enhanced PSH technologies (with efficiency up to 85%) are characterized by medium-high efficiency, together with a low cost per kWh. Notwithstanding its large environmental impact, PSH is the currently most installed energy storage technology. With reference to the Italian scenario, PSH is of great interest in consideration of the results of the study carried out by the European Joint Research Centre [32]. This study highlights the possibility to realize new pumped hydro storage systems in Italy by exploiting already existing reservoirs (with minimum capacity of 100.000 $m^3$ of water) through suitable retrofitting. In particular, considering the cases with two reservoirs or only one already existing, under all the other assumptions made in [32], a storage capacity of about 4,700 GWh arises. This solution allows a significant mitigation of PSH environmental impact and a further reduction in capital costs.

Aiming to briefly analyze the batteries types, it is possible firstly to classify them according to the electrolyte solution used (lead-acid, Na–S, Ni–Cd,  Ni–MH, Li-ion).

Lead-acid (Pb-acid), Na–S, Ni–Cd and Ni–MH batteries can all be considered mature technologies. Pb-acid batteries are overcome by the others as far as their weight, their low specific energy and power with a short cycle life, and their high maintenance requirements are concerned. Na–S batteries are characterized by an excellent cycle life, high energy density but, currently, their cost and the self-discharge per day remain very high. Ni–Cd and Ni–MH technologies have a higher energy density and maintenance requirements than Pb-acid batteries, but their diffusion is still limited by their high costs. Lithium ion (Li-ion) batteries have a high energy to weight ratio, no memory effect and low self-discharge. Disadvantages include high cost, safety implications and the need of sophisticated battery management [33]. In general, battery technology is still affected by high cost per kWh and further critical issues relative to environmental impact and duration [34].

## 3.2 European framework overview

In the European energy context, the energy storage potential is closely related to policy on renewable electricity. Member States are characterized by different interests and potentials in energy storage together with various stages of development. Today in EU, technology development is very slow due to the poor economic/business case and related uncertainties. However, EU thanks to its role of spur in technological cooperation could improve the market conditions and the R&D activities.

Actually a not shared regulatory framework between Members States creates a difficulty in the development of energy storage systems. In fact, globally, only few States (Austria, Czech Republic, Germany, Hungary, Ireland, Poland, Slovakia) adopted a regulation related to energy storage, but it is specifically only for the natural gas storage. In particular, for the Italian case, there are no specific regulation regarding any kind of energy storage. Currently, the energy storage systems connected to the grid have to respect the relative regulation for the connection of a generator to the distribution grid (CEI 0-21 for LV connection and CEI 0-16 for MV and HV connection). As a consequence of this European legislative indeterminacy, a definite regulatory framework should create an equal level playing field for cross-border trading of electricity storage. Specifically, in order to integrate storage into markets, it is fundamental to provide clear rules and responsibilities concerning the technical modalities and the financial conditions. Moreover, the regulatory framework has to guarantee a level playing field regarding other sources of generation, exploit its flexibility in supplying the grid, stabilise the quality and supplies for RES. In this way, it could spur to improve the business/economic model for energy storage.

So, considering the EU energy and climate policy (the internal market, EU2020 and 2050 targets and infrastructure priorities), EU policy needs to establish clear and consistent indications to technology developers, industry and consumers. In particular, the optimisation of the power system and the synergies between the existing system and storage technologies must be explored and promoted. In [2] a list of urgent actions useful to the deployment of storage on EU is provided. In particular, it refers to: strategic actions, consumer and market issues, regulatory topics and technological and investment support.

In conclusion, a stronger focus on storage in EU energy and climate policies is needed, also in order to improve the coordination between storage topic and other key policy issues. Energy storage has to be integrated into, and supported by, all relevant existing and future EU energy and climate measures and legislation, including strategies on energy infrastructure (Horizon 2020; 2050 Roadmap [1]).

### 3.3 ESS-CC solution: quantitative analysis

In Table 3 the operating data for CC plants with and without CHP are provided. Specifically, for CC-CHP plants the year 2012 was taken as reference for performance evaluation. It is important to underline as CC-CHP plants, in terms of equivalent hours in 2012, worked 2.6 times more than the other ones. It corresponds also to an operation closer to the nominal conditions as demonstrated by a CC-CHP electric efficiency of 54.6%. This value is remarkable since, in the same year, CC plants with only electricity production exhibited an efficiency of 51.1%.

Figure 14 shows the almost linear dependence between electric efficiency and equivalent operating hours (except for 2010). Therefore, with reference to the operation mode of CC plants in the period 2008-2012, the assumption of a particular $H_{eq}$ is strongly related to a characteristic electric efficiency. So, 5,067 $H_{eq}$ correspond to 54.6% efficiency, considered as the target for CC technology. Under this assumption, the electricity production of 2012 ($P_{CC\_2012}$ of 50,652 GWh) could be satisfied by only 9,996 MW of CC plants vs. 25,408 MW actually operated in 2012 under 51.1% efficiency.

**Figure 14 CC electric efficiency Vs equivalent operating hours**

Moreover, the mean delivered power ($M_{dp}$) to satisfy the electricity production $P_{CC\_2012}$ was calculated by Eq.2 with reference to the CC equivalent operation hours for each year in the period from 2008 up to 2012, as indicated in Table 3.

$$M_{dp} = \frac{P_{CC\_2012}}{H_{eq}} \tag{2}$$

In the last table row, ratio between $H_{eq}$ of CC and CC-CHP plants, taken as reference, is calculated.

**Table 3 CC and CC-CHP plants performance comparison**

It's clear that inducing the CC plants to work close to nominal conditions, and then at higher efficiencies, allows a considerable annual saving in terms of consumed primary energy. In fact, considering an efficiency equal to 54.6%, a saving of about 6,200 GWh (92,822 rather than 99,065 GWh) could be achieved to satisfy the production $P_{CC\_2012}$. This corresponds to a percentage reduction of 6.3% with respect to the actual consumption to a 51.1% efficiency.

Obviously, the operating management of CC plants indicated above, even if satisfying the global energy demand of 2012, probably does not meet the constraints relative to the thermoelectric plants location on the electric grid. In fact, it implies a definitive shut-off of CC plants corresponding to about 60% of power actually operated in 2012 (25,408 MW). Due to the elongated shape of the Italian territory and the consequent structure of the national electric grid, a suitable number of power plants must be kept on operation for balance of grid sections.

For those reasons, it is necessary to introduce ESS to allow a postponed usage of the produced energy. ESS integration implies an energy cost, which increases with the energy rate to be stored in comparison with the annual total production and depends also on the efficiency of the considered storage technology. Therefore, the additional energy consumption, necessary for ESS integration, was calculated through a sensitive analysis by varying energy rate to be stored and ESS efficiency. Main storage technologies are included, i.e. CAES (70% efficiency [31]), PSH and enhanced PSH (70-85% efficiency [2], [31]) and ESB (energy storage battery with 90-95% efficiency [31]).

With reference to Table 4, which summarizes the results of this analysis, all the cases (highlighted in grey) with an additional consumption lower than 6,200 GWh, corresponding to the energy saving due to the CC high-efficiency operation, are of interest. Clearly, by increasing the ESS efficiency, the amount of energy, which can be conveniently stored, also grows.

**Table 4 Energy consumed for energy storage**

The implementation of the ESS penetration scenario of Table 4 needs of a suitable management strategy of the CC plants. To investigate the proper strategy and the impact of ESS integration in terms of energy saving, in the following, a particular case is considered as example.

Specifically, ESS capacity corresponding to 30% of $P_{CC\_2012}$ (15,196 GWh) and ESS efficiencies of 85% were assumed. The latter value is compatible with the use of ESB technologies, being below their efficiency values [2], [36], [31]. Furthermore, in relation to the PSH systems, which currently constitute nearly all of the existing storage facilities, the considered performance value corresponds to the upper efficiency bound characteristic of the current technology as indicated in [2], [36]. In relation also to the improvements expected in the short and medium term [2], as indicated in the Technology Map of the European SET-Plan [31] mainly regarding the use of generation equipment with improved efficiency, this value can be considered plausible for possible future applications.

Taking into account the storage efficiencies indicated above, the surplus of electric energy needed by ESS operation was evaluated in 2,682 GWh (5.3% of $P_{cc\_2012}$). This value corresponds to an overall production ($P_{cc}$) of 53,334 GWh vs. 50,652 GWh actually produced in 2012 by CC.

In order to guarantee the $P_{cc}$ data indicated above with a CC plants efficiency of 54.6%, the proposed operation strategy implies the shutoff of 43.8% thermoelectric plants, in terms of current capacity. In particular, the ESS penetration, in the measure indicated above, allows to have 14,280 MW working for 3,547 $H_{eq}$ under 54.6% efficiency, instead of 9,996 MW with an operation time of 5,067 $H_{eq}$ calculated without ESS. In fact, 30% of stored energy ($E_{st}$) with respect to $P_{cc\_2012}$ is determined as (Eq.3):

$$E_{st} = \frac{[14{,}280(MW) - 9{,}996(MW)] \cdot 3{,}547(h)}{P_{CC_{2012}}(MWh)} \tag{3}$$

Therefore, ESSs allow to have a larger number of CC plants in operation (equal to about 56% of the installed power) at a higher efficiency (54.6%) with a smaller $H_{eq}$ (as evident in Figure 14 which depicts the $H_{eq}$ – efficiency correlation characteristic of CC plants working without ESS), ensuring the same total production (increment of 5.3%). This allows a greater flexibility relative to both actual demand profile and thermoelectric plants location with respect to the territorial grid layout.

The primary energy saving characteristic of the investigated case can be assessed through the determination of the CC energy input, as $P_{cc}$/54.6%, and the calculation of the gap with respect to the 99,065 GWh consumed in 2012 under actual operation conditions. This procedure results in a primary energy saving of 1,329 GWh for the particular case considered as example. It corresponds to an annual saving of $138 \cdot 10^6$ $Sm^3$ of natural gas, rather than about 100 M€/year and 84 M€/year, considering for the natural gas the mean National Single Price PUN value of 2012 (75.48 €/MWh) and 2013 (62.99 €/MWh) respectively [27].

Moreover, it is important to quantify the avoided wear-and-tear costs due to cycling operation. As shown in [36], these costs for the average fossil-fuelled plant could be quantified in € 0.36 to € 1 per MWh of fossil-fuelled generation. Therefore, considering the entire annual production of $P_{cc\_2012}$, a further saving of about 18.5 to 50.2 M€/year can be reached by adopting the ESS-CC solution.

The presented analysis was focused on one possible example to evaluate, relative to the Italian thermoelectric sector, the gross effect of ESS-CC coupling. It has not to be considered as a full economic study of the ESS-CC solution, since it addresses only the evaluation of energetic and economic advantages related to a more performant CC operation in terms of both efficiency and wear-and-tear damage. Obviously, additional and more accurate analysis are needed to evaluate the actual feasibility of this strategy.

# 4 Conclusions

This paper addresses the impact of renewable sources on the Italian thermoelectric sector. This scenario is characterized by a quick and significant RES growth without a suitable regulatory framework contributing to ESS integration in the national energy system.

In particular, the drop in thermoelectric efficiency occurred in Italy in the period 2008-2012 is deeply analyzed, quantified and related to the RES growth in the same period. Specifically, in the absence of a regulatory framework concerning ESS integration and under a contextual trend of the energetic commodities bringing to a greater use of lower quality fuels (i.e. coal), a decrease in the thermoelectric generation efficiency, mainly due to CC operation management, is observed.

This performance degradation is evaluated, with respect to a reference operation modality (54.6% yearly mean efficiency), in about 6,200 GWh of energy penalty with reference to the energy production of CC plants in 2012. This consumption penalty corresponds to the 6.3% of the corresponding natural gas consumption.

To mitigate this inefficiency, the integration of ESS is preliminarily investigated aiming to operate CC plants in conditions (reference operation modality as indicated above) closer to the nominal ones and avoiding their functioning as backup power of RES plants.

Therefore, pointing on the strategy of integrating storage technology with the operation of thermoelectric plants and, specifically, reviewing the CC operating conditions, the impact of possible ESS coupling with CC plants is quantified through a sensitivity analysis. The percentage of the yearly stored energy and the ESS efficiency are considered as the variation parameters. Among all the resulting solutions, a possible scenario is analyzed, corresponding to a 30% rate of stored energy with respect to $P_{CC\_2012}$ and 85% of ESS efficiency value.

The need to shut-down part of CC installed power (about 44%), depending on the produced energy rate (30%) to be stored, is demonstrated to guarantee CC plants working as long as possible at nominal operating conditions. Under these assumptions and in order to satisfy the $P_{CC\_2012}$ production, energy savings of about 1.5% of the CC plants consumption in 2012 are obtained. Another advantage is the reduction on wear-and-tear damage. Considering that the amount of wear-and-tear costs due to plant cycling are valued in the range 0.36-1 €/MWh, about 18.5 to 50.2 M€/year can be saved relative to O&M costs additionally to about 100 M€/year due to the energy saving indicated above.

These assessments, carried out with a simplified analysis for a particular example case, can be further improved at a national level and expanded at an international level, but they are strongly affected by the expected improvements of ESS technologies mainly relative to the reduction in their capital cost. What this study clearly showed is that further introduction of either programmable or unprogrammable RES requires a strong strategic decision on investing in ESS, to avoid operating large CCs at lower efficiency and increasing the use of coal instead of natural gas.

Also improvements of the regulatory framework are strongly expected contributing to perspectives of profitable storage operation. In this framework, a first regulation could impose the installation of an ESS for each new large scale unprogrammable renewable power plant.

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**Title:** Challenges in load balance due to renewable energy sources penetration: the possible role of energy storage technologies relative to the Italian case

## Abstract

With the rapid growth of the electricity produced by renewable energy sources (RES), especially those highly variable and unprogrammable (e.g. wind and solar power), the need of energy system flexibility increases significantly.

Since RES currently represent a significant fraction of the power supply, their variable nature poses challenges to power grid operation, such as RES curtail and loss in global efficiency of thermoelectric plants, since they are often operated at part-load as fluctuating back-up power.

In particular, thermoelectric plants recently moved their role from base-load power to fluctuating back-up power. Such a cycling operation represents a less obvious effect of grid flexibility requirement due to RES penetration. Main effect is the increment of both energetic costs, due to reduced efficiency operation, and wear-and-tear costs.

This aspect is deeply analyzed in reference to the Italian electricity generation mix in the period 2008-2012. Moreover, the possible coupling of energy storage systems with thermoelectric plants is highlighted as an alternative solution respect to retrofitting of existing plants.

## Keywords

Plant flexibility; plant cycling; energy storage; grid imbalance

## Nomenclature

| | | |
|---|---|---|
| $E_{st}$ | energy stored | (MWh) |
| $H_{eq}$ | equivalent operating hours | (h) |
| $M_{dp}$ | mean delivered power | (MW) |
| $P_{CC}$ | electricity production | (GWh) |
| $P_{CC\_2012}$ | electricity production of 2012 | (GWh) |
| $P_g$ | gross electricity production | (GWh) |
| $W_g$ | gross installed power | (GW) |

## 1 Introduction

In the next years, a rapid growth of renewable sources exploitation is foreseen in order to cover with renewable sources up to 20% of the final energy consumption in 2020 and an even larger share by 2050 [1]. In fact, RES technologies are expected to take the leadership in the forthcoming energy generation portfolio in order to achieve a sustainable energy generation. Anyway, their utilization is slowed down by the characteristic intermittency and the fluctuating trend and, moreover, by the inadequacy of electricity networks. To ensure such a penetration, electricity systems need to be flexible in order to balance at every moment generation and consumption.

In some European countries (Denmark, Spain and Germany) the renewable energy share has already exceeded 20% [2], highlighting critical issues such as grid congestion and perturbation [3],[4] due to the large number of highly unpredictable, intermittent and fluctuating power plants [5]. Moreover, in order to mitigate the serious concerns indicated above, RES are curtailed during low consumption periods limiting the exploitation of renewable power plants.

What above represents the critical issues, relative to the RES exploitation, usually analysed in literature [6]-[10] together with the possible solution identified in energy storage systems (ESS) integration, mainly contributing to:

- grid reliability improvements thanks to the reduction in both fluctuating energy delivered to the grid and energy absorption from the grid (leading to mitigation of grid overload);
- reduction in curtailment of unprogrammable renewable energy generation due to network constraints;
- deferring investments of grid improvement.

A further negative aspect to overcome is the RES impact on thermoelectric power generation. In literature, few articles deal with RES implications on conventional power generation; however, some specific studies on wind variability and its effect on traditional generators are available. A model to estimate emissions from fossil fuel generators used to compensate variable wind and solar power is presented in [11]. Specifically, a quantification of $CO_2$ and NOx emission is provided considering natural gas turbine as power technology used to compensate variable renewables. An interesting model of wind/gas/energy storage generation systems, described in [12], demonstrates a method for integrating significant quantities of wind energy while reducing power fluctuations, showing the financial feasibility of the solution in relation to the produced wind energy.

In the present paper, the particular issue of RES impact on conventional power generation is analysed with particular attention to the Italian scenario. As detailed in the following, in order to overcome the grid balance problem due to the difference between energy generation and consumption, part of the Italian thermoelectric plants were managed in the last years as backup of RES. The consequent significant negative effects on thermoelectric generation performance are deeply investigated in this work. In fact thermoelectric plants, with particular reference to combined cycles (CC), are operated as part-loaded plants, which can be ordered to increase or decrease output as required, and generally subjected to hot and cold stand-by periods. This cycling operation causes a significant reduction in electric efficiency (CC plants exhibit the greatest efficiency degradation when operated in part-load conditions [13],[14]) and thermal/pressure stresses resulting in a relevant wear-and-tear damage [15], [16]. These aspects bring about an increasing of fuel costs and O&M costs due especially to more frequent repairs, reduced component life and more frequent forced outages [15]-[18].

Therefore the cycling aspect, or rather the power output variation due to starting up, shutting down, ramping up and down [17], is a central issue consequent to the increasing penetration of RES in the electricity generation system [19].

During power plant cycling, as anticipated, components suffer of large temperature and pressure stresses than lead to accelerated component failures and forced outages [18]. Consequently, costs associated with power plant cycling, widely studied in literature [17],[20],[21], are due to five significant components [20]: capital replacement costs and maintenance cost, cost of forced outages due to cycling, capital replacement costs and maintenance cost related to load following, cost for fuel, $CO_2$ emissions and auxiliary services during start-up, beyond that cost for decrease in rated efficiency.

For what above the research of solutions that can mitigate problems caused by cycling became crucial. To this regard, preclusions relate to any solution that requires the construction of new power plants, due to the already too large installed power and further curtailment of RES. Therefore, the most plausible solutions are identified to act directly on the existing power generation facilities. A potential approach is, in fact, the retrofitting of existing power plant [22]. Recent improvements [23] regard the operation flexibility enhancement (i.e. faster re-start and ramp faster within a wider load range) and, preliminarily, solutions to increase efficiency at part load and mitigate thermal and pressure modulation varying load condition [24].

Therefore, in this paper an alternative solution is proposed and preliminarily analysed. In particular, the energy storage systems (ESS) integration with large thermoelectric plants (specifically combined cycles) is proposed. This solution could allow operation in conditions closer to the nominal ones, obviously reducing cycling and consequent penalties indicated above. In other words, the energy surplus generated by CC plants, that can work close to nominal conditions, can be stored by ESS avoiding their continuous shutdown and restart.

At system level, no previous studies are available regarding the analysis and quantification of efficiency penalization on the thermoelectric sector due to RES penetration. In the research work herein presented, CC plants part-load operation, as RES backup, and related efficiency are evaluated by using quantitative parameters. In particular, the analysis is carried starting from the analysis of operation data of the whole Italian thermoelectric power generation sector with reference to the period 2008-2012 (Section 2), by analyzing performance of single plant technologies (Section 3). Consequently, the impact of RES exploitation on the thermoelectric generation efficiency is evaluated, relative to the Italian case, in terms of primary energy penalty. Basing on these results, a reference management strategy of CC plants is identified (Section 4); moreover the impact of their possible coupling with ESS is quantified limited to the advantages related to fuel and wear-and-tear costs.

# 2 Material and data analysis

## 2.1 Analysis of production and fuel consumption of the whole thermoelectric power generation sector

In this section data relative to installed power and energy production of systems connected to the Italian grid are described and analyzed. The source is the annual reporting of Terna, the Italian energy Transmission System Operator (TSO). Specifically, reports relative to the years from 2008 to 2012 were considered. In this period, the number of unprogrammable renewable power plants increased considerably.

To this purpose, Figure 1 shows the trend of the installed power in the period from 2008 up to 2012. As it can be seen, against a general invariance of thermoelectric and hydroelectric installed power and against a slight gain in the wind energy exploitation, there is a significant increase in photovoltaic (PV) power installations, which grows from 430 MW in 2008 up to 16,420 MW in 2012. Cause of this trend can be related to the important policy mechanism, introduced by Italian Government in February 2007 [25]-[28], designed to accelerate investment in PV technology with a feed-in premium. This incentive campaign ended in July 2013 (for new installations) with the simultaneous depletion of state funds allocated to incentivize those power plants.

**Figure 1 Installed net power in Italy: 2008-2012**

Within the thermoelectric sector, as highlighted in Figure 2, combined cycle (CC) technology has the leading role with a higher than 45% share of the installed capacity in the years 2011-12. Moreover, it can be noted that the installed capacity of condensing steam turbine plants (CST) dropped by 5%, from 2008 to 2012, whereas the installed capacity of repowered power plants (RP), gas turbines (GT) and internal combustion engines (ICE) was left unchanged.

Even with such a sharp decline in installed capacity CST power plants are still the second power generation technology in Italy.

**Figure 2 Percentage of gross installed capacity of each plant technology**

In order to further analyse the evolution of the thermoelectric sector in the observed period, data about production, consumption and efficiency are provided hereinafter. Figure 3 and Figure 4 show, respectively, gross and net produced electric energy for each kind of fuel used in thermoelectric plants. For clarity, gross production is the amount of electricity produced, measured at the terminals of electric generators. Instead net production is the amount of electricity produced, measured at the border of power plants, i.e. deducting the amount of electricity necessary for auxiliary services. From these two figures, it is clear how the use of natural gas is far larger than all other fuels. In particular, considering that the amount of energy produced by natural gas is 4 times as large as that produced by solid fuels, it is easy to conclude how Italian energy production is strongly dependent on natural gas supplies. This is also clear considering the energy consumption data distinguished by fuel type as shown in Figure 5.

**Figure 3 Gross produced electric power from thermoelectric plants in Italy: 2008-2012**

**Figure 4 Net produced electric power from thermoelectric plants in Italy: 2008-2012**

**Figure 5 Consumed fuel for thermoelectric plants typology in Italy: 2008-2012**

However, it is important to emphasize that from 2008 to 2012, there was a noticeable drop in natural gas consumption, mainly due to the reduction in the use of this kind of plants (principally combined cycles fed by natural gas) with a consequent decline in their production. In fact, it can be considered that the decrease in petroleum products was compensated by the increase of solid fuels utilization, which is the logical consequence of the conversion of most oil fuelled thermoelectric plants to coal. This trend was also accelerated by the fall of coal price occurred in 2012 (Figure 6).

**Figure 6 International prices of major energy commodities 2008 – 2012 [26]**

In consideration of what described above and due to the higher price of natural gas, in the period 2008-2012 CC plants were mainly operated to compensate the RES growth occurred in the same period, with a relevant decrease in their annual operating hours, as discussed in the following. The effect of the RES growth influences substantially natural gas CC since:

- from a technological point of view, CC are characterized by a greater flexibility if compared to steam plants fed by solid fuels,
- although CC plants are characterized by greater energy efficiency, they are penalized, as said above, by a higher cost of generation due to the high natural gas cost.

Moreover, analysing the global production and the consumption data, it is also clear how the mode of operation of those plants was changed from base-load to the current mode as fluctuating back-up power. The main effect, always with reference to the period 2008-2012, can be found in the electric efficiency trend of CC plants fed by natural gas. In fact, as discussed in Section 3, a significant decrease in their efficiency can be justified, at first glance, by their sub-optimal functioning. In general, CC plants operating time decreased, with power output increasingly far away the nominal one. In Section 3 the issues relating to CC management are discussed, with reference to the period of analysis indicated above.

It is clear, therefore, that the management strategy of combined cycle produces a significant efficiency penalty with effects on the whole thermoelectric sector, with the exception of combined heat and power plants (CHP), as shown in Figure 7.

**Figure 7 Thermoelectric plants efficiency without CHP in Italy: 2008-2012**

In fact, referring to Figure 7, relative to thermoelectric plants with only electricity production, gross and net efficiency decline of about 0.8 and 1.1%, respectively, from 2011 to 2012. This decline is more pronounced considering the five years under analysis; indeed gross and net efficiency moves from 43.6% and 41.4% in 2008 to 42.3% and 39.7% in 2012. It is interesting to emphasize as this decline corresponds to an increase in the difference between gross and net efficiency, which in 2012 reached the maximum value (with respect to the period of analysis) of 2.6%, suggesting an increasing incidence of auxiliary services on the energy production. This feature, which will be analysed in detail below, is indicative of a growth of part-load operation of power plants.

To prove the negative effect of CC plants management on the global thermoelectric efficiency, it can be noted, with reference to Figure 8, that, if we include CHP plants, the overall decline in thermoelectric performance is lower. Namely, a gross and net efficiency of the overall thermoelectric sector of 46.5% and 44.5% and of 46.2% and 44.0% was measured in 2008 and 2012, respectively.

In fact, with respect to the fluctuating back-up power operation which is now common in CC plants without heat production, CHP plants are characterized by a more continuous operation normally much closer to nominal conditions. This is consistent with their operation in heat tracking mode, not following changes in the power demand from the grid.

**Figure 8 Thermoelectric plants efficiency with CHP in Italy: 2008-2012**

## 2.2 Performance analysis of single technologies

Aiming at further analysing the performance of the thermoelectric sector, it is useful to investigate the actual energy production and the efficiency trends of each energy conversion technology. Also in this case, the source is the annual reporting of Terna, with particular reference to the years from 2008 to 2012.

Starting from the analysis of the gross and net production data, shown in Table 1, it is quite evident that CC technology, or rather the one that guarantees the highest annual production, has produced 40% less energy in 2012 than in 2008, operating far from its nominal power potential. This downward trend is crucial to understand the global plant performance. As it can be seen in Figure 9 andFigure 10, the efficiency of combined cycles is far from typical values of this technology. In particular CC plants, from 2008 to 2012, have lost 1.6 and 1.8% of the gross and net efficiency, reaching values of 52.7% and 51.1%. Moreover, still for CC systems, the gap between the gross and net efficiency values gets larger in the years when the energy production is decreased due to the larger weight of fixed plant energy consumption (i.e. auxiliary service).

**Table 1 Energy production for each power plant technology**

Furthermore, in Figure 9 and Figure 10 it is not possible to identify a common efficiency trend for the different plant technologies. In general, compared to a slight efficiency increase in internal combustion engines (ICE) and condensing steam turbine (CST) plants, a considerable efficiency decrease in gas turbine (GT) and an efficiency drop of re-powered plants (RP) and combined cycles (CC) is observable. It is remarkable that GT, RP and CC plants cover about 60% (over 45% by CC technology) of the total installed thermoelectric power in Italy. Consequently, the global thermoelectric efficiency has decreased in the studied period, as highlighted in previous Section 2 (Figure 7).

**Figure 9 Plants gross efficiency sorted by technology in Italy: 2008-2012**

**Figure 10 Plants net efficiency sorted by technology in Italy: 2008-2012**

As mentioned above, the increased number of hours of part-load operation of these facilities (in particular CC plants) with consequent performance drop, is undoubtedly related to the increase of RES power generation.

Thanks to the campaign of state incentives, mentioned at Section 2, the energy introduced into the grid provided by PV system is increased from almost zero in 2008 to about 19,000 GWh in 2012 (Figure 11). This situation should not be considered isolated from the rest of Europe. For example in Spain, due to the aggressive incentive campaign, the PV production has moved from a 490 GWh in 2007 to about 8,500 GWh in 2012 [4].

**Figure 11 Gross produced electric power for RES in Italy: 2008-2012**

Relative to the Italian case, this increase, along with the simultaneous growth of the produced energy by wind generators (about 10,000 GWh in the period of study), is comparable with the decreased production from CC plants. As further proof of this fact, it is also interesting to analyze the equivalent operating hours ($H_{eq}$) of both thermoelectric power plants (Figure 12) and renewable power plants (Figure 13), with particular reference to wind and PV plants.

**Figure 12 Thermoelectric plants: equivalent operating hours**

**Figure 13 Wind power and PV equivalent operating hours**

For each plant typology, the equivalent operating hours were calculated according to Eq.1.

$$H_{2eq} = \frac{P_g}{W_g} \tag{1}$$

In terms of operating hours, it is possible to observe from 2008 to 2012 a continuous decrease of the use of CCs and a similar increase of photovoltaic and wind energy. The reduction of CC energy production is mainly due to the RES priority of power dispatch to the grid. This means that, in response to a possible decrease in the power demand from grid, the thermoelectric generation has to lower its power output instead of excluding RES production. In particular, the trends depicted in Figure 13, since they represent the ratio between energy production and installed power (Eq.1), correspond to a progressive reduction of wind and PV plants curtailment. This is only possible by switching the operation of CC power plants from base-load to fluctuating back-up power.

In particular, as detailed in Table 2, in the period of study CC equivalent operating hours are halved (from about 4,000 in 2008 to about 2,000 in 2012). The reduction in the operation of RP plants, which were almost totally stopped in the last years, is also significant. The effects of this management strategy must be analyzed also considering the importance of CC and RP plants (about 55% of the installed power in Italy), on the Italian thermoelectric sector (not including CHP plants).

On the other hand, the operation of CST plants is almost unchanged as shown in Figure 10, even though their efficiency is 20 percent points lower than that of CC power plants. This strategy, which implies important energy penalties, was motivated by the lower price of coal, progressively more used in the investigated period consequently to the conversion of the main oil thermoelectric plants.

**Table 2 $H_{eq}$ calculated on the basis of gross production and installed power data**

The reduction in $H_{eq}$ for CC plants is characteristic of their actual use in low load conditions or even shutdown. These operating conditions are far from the optimum operating point, leading, as mentioned above, to a significant efficiency drop. Consequently, it can be asserted that it is necessary to review the utilization of thermoelectric plants in this current scenario strongly influenced by RES. In particular, a strategy, based on ESS coupling to CC plants, is presented in Section 4 to guarantee the CC operation as possible at nominal and steady load.

# 3 Results and discussion

## 3.1 ESS-CC solutions: background & approach

As seen in the previous section, government policies to encourage the diffusion of RES technology (mainly PV), not accompanied by a plan for the electricity grid improvement (including widespread use of ESS) and economic choices, pushing for the use of lower quality fuels (i.e. coal) has led to a substantial decrease of the energy performance of Italian thermoelectric power plants. This is caused mainly by a reduction in operation natural gas plants, such as CC (characterized by the highest efficiency) and their management as fluctuating back-up power to compensate RES production trend, therefore under conditions far away from the optimal ones. Moreover, the energy free market has opened the production of energy to a number of plant operators, who have their own strategies and maintenance scheduling, and a national planning to promote the highest efficiency of the electricity mix seems to be no longer possible.

The current Italian RES capacity, including hydro, geothermal, biomass, wind and solar energy can theoretically satisfy the peak demand without any additional thermoelectric power. Due to the capacity factors of unprogrammable RES, this is not possible, but since a large share of CHP is now in operation, the need for power plants dedicated to electric energy production is now much smaller than in the past.

Any additional RES capacity could clash with the operation of CHP power plants, and reduce the other thermoelectric power plants to a minimal share of energy production. The Italian electricity mix would then be completely rearranged in a way that was totally unexpected just a few years ago. There is therefore a strong need of systems that allow storing energy or improve the energy management and utilization during the days and the year.

Therefore, an important topic can be identified in the development of energy storage technologies, pointing on the strategy of integrating storage technology with the operation of thermoelectric plants and, specifically, reviewing the CC operating conditions. This strategy, in addition to the development of fossil power plants characterized by higher flexibility and sufficiently high efficiency in a wide range of part-load operation, could positively contribute to the efficiency improvement of the entire thermoelectric sector, allowing CC plants operation at nominal conditions and postponing the utilization of the produced energy to follow the demand. To this purpose, an overview of ESS technology and the scenario of ESS integration with CC plants were hereinafter shown.

ESS technologies can be classified in four categories: mechanical, electrical, thermal and chemical. Each category offers different opportunities, but also features some disadvantages.
A further distinction must be made between technologies for "power" applications (delivery of electricity for short periods) and those for "energy" applications (delivery electricity for medium and long periods). As an example, flywheel, supercapacitors and superconducting magnetic energy storage (SMES) are power technologies, while batteries (mainly Na/S and redox batteries as mature and first stage technology respectively), compressed air energy storage (CAES) and pumped-storage hydroelectricity (PSH) are energy technologies.
Even if a large number of technologies are well known or already under development, only a very limited storage capacity is integrated in the European scenario, assessed at around 5% of total installed capacity [2]. Moreover, specifically for "energy" applications, ESS technologies different from Pumped Hydro energy Storage (PSH) (i.e. sodium–sulphur batteries, compressed air energy storage, thermal energy) are minimally integrated. However CAES and some kind of batteries are characterized by a mature level. In the following, some details are provided about ESS technologies for "energy" applications, i.e. CAES and PSH, among mechanical technologies, and batteries.

CAES technology is based on the use of the excess energy to compress air into underground caverns or storage tanks. During discharge, the compressed air expands in a turbine, after the passage through a possible combustion chamber (where natural gas is burned) or a heat recovery system (AA-CAES, efficiency of about 70%) [5], [29]. Considering CAES installation cost and its moderate energy density [30], it is currently suitable only at large scale (>100 MW). Expected improvements, as indicated in [31], are CAES downscale to the MW order of magnitude allowing  the "any site" location (compressed air can be stored in fabricated high-pressure tanks, making ESS location independent of geology) and the development of new simplified high-pressure air turbines with high efficiency, specifically designed for this application.

PSH and enhanced PSH technologies (with efficiency up to 85%) are characterized by medium-high efficiency, together with a low cost per kWh. Notwithstanding its large environmental impact, PSH is the currently most installed energy storage technology. With reference to the Italian scenario, PSH is of great interest in consideration of the results of the study carried out by the European Joint Research Centre [32]. This study highlights the possibility to realize new pumped hydro storage systems in Italy by exploiting already existing reservoirs (with minimum capacity of 100.000 $m^3$ of water) through suitable retrofitting. In particular, considering the cases with two reservoirs or only one already existing, under all the other assumptions made in [32], a storage capacity of about 4,700 GWh arises. This solution allows a significant mitigation of PSH environmental impact and a further reduction in capital costs.

Aiming to briefly analyze the batteries types, it is possible firstly to classify them according to the electrolyte solution used (lead-acid, Na–S, Ni–Cd,  Ni–MH, Li-ion).

Lead-acid (Pb-acid), Na–S, Ni–Cd and Ni–MH batteries can all be considered mature technologies. Pb-acid batteries are overcome by the others as far as their weight, their low specific energy and power with a short cycle life, and their high maintenance requirements are concerned. Na–S batteries are characterized by an excellent cycle life, high energy density but, currently, their cost and the self-discharge per day remain very high. Ni–Cd and Ni–MH technologies have a higher energy density and maintenance requirements than Pb-acid batteries, but their diffusion is still limited by their high costs. Lithium ion (Li-ion) batteries have a high energy to weight ratio, no memory effect and low self-discharge. Disadvantages include high cost, safety implications and the need of sophisticated battery management [33]. In general, battery technology is still affected by high cost per kWh and further critical issues relative to environmental impact and duration [34].

## 3.2 European framework overview

In the European energy context, the energy storage potential is closely related to policy on renewable electricity. Member States are characterized by different interests and potentials in energy storage together with various stages of development. Today in EU, technology development is very slow due to the poor economic/business case and related uncertainties. However, EU thanks to its role of spur in technological cooperation could improve the market conditions and the R&D activities.

Actually a not shared regulatory framework between Members States creates a difficulty in the development of energy storage systems. In fact, globally, only few States (Austria, Czech Republic, Germany, Hungary, Ireland, Poland, Slovakia) adopted a regulation related to energy storage, but it is specifically only for the natural gas storage. In particular, for the Italian case, there are no specific regulation regarding any kind of energy storage. Currently, the energy storage systems connected to the grid have to respect the relative regulation for the connection of a generator to the distribution grid (CEI 0-21 for LV connection and CEI 0-16 for MV and HV connection). As a consequence of this European legislative indeterminacy, a definite regulatory framework should create an equal level playing field for cross-border trading of electricity storage. Specifically, in order to integrate storage into markets, it is fundamental to provide clear rules and responsibilities concerning the technical modalities and the financial conditions. Moreover, the regulatory framework has to guarantee a level playing field regarding other sources of generation, exploit its flexibility in supplying the grid, stabilise the quality and supplies for RES. In this way, it could spur to improve the business/economic model for energy storage.

So, considering the EU energy and climate policy (the internal market, EU2020 and 2050 targets and infrastructure priorities), EU policy needs to establish clear and consistent indications to technology developers, industry and consumers. In particular, the optimisation of the power system and the synergies between the existing system and storage technologies must be explored and promoted. In [2] a list of urgent actions useful to the deployment of storage on EU is provided. In particular, it refers to: strategic actions, consumer and market issues, regulatory topics and technological and investment support.

In conclusion, a stronger focus on storage in EU energy and climate policies is needed, also in order to improve the coordination between storage topic and other key policy issues. Energy storage has to be integrated into, and supported by, all relevant existing and future EU energy and climate measures and legislation, including strategies on energy infrastructure (Horizon 2020; 2050 Roadmap [1]).

### 3.3 ESS-CC solution: quantitative analysis

In Table 3 the operating data for CC plants with and without CHP are provided. Specifically, for CC-CHP plants the year 2012 was taken as reference for performance evaluation. It is important to underline as CC-CHP plants, in terms of equivalent hours in 2012, worked 2.6 times more than the other ones. It corresponds also to an operation closer to the nominal conditions as demonstrated by a CC-CHP electric efficiency of 54.6%. This value is remarkable since, in the same year, CC plants with only electricity production exhibited an efficiency of 51.1%.

Figure 14 shows the almost linear dependence between electric efficiency and equivalent operating hours (except for 2010). Therefore, with reference to the operation mode of CC plants in the period 2008-2012, the assumption of a particular $H_{eq}$ is strongly related to a characteristic electric efficiency. So, 5,067 $H_{eq}$ correspond to 54.6% efficiency, considered as the target for CC technology. Under this assumption, the electricity production of 2012 ($P_{CC\_2012}$ of 50,652 GWh) could be satisfied by only 9,996 MW of CC plants vs. 25,408 MW actually operated in 2012 under 51.1% efficiency.

**Figure 14 CC electric efficiency Vs equivalent operating hours**

Moreover, the mean delivered power ($M_{dp}$) to satisfy the electricity production $P_{CC\_2012}$ was calculated by Eq.2 with reference to the CC equivalent operation hours for each year in the period from 2008 up to 2012, as indicated in Table 3.

$$M_{dp} = \frac{P_{CC\_2012}}{H_{eq}} \tag{2}$$

In the last table row, ratio between $H_{eq}$ of CC and CC-CHP plants, taken as reference, is calculated.

**Table 3 CC and CC-CHP plants performance comparison**

It's clear that inducing the CC plants to work close to nominal conditions, and then at higher efficiencies, allows a considerable annual saving in terms of consumed primary energy. In fact, considering an efficiency equal to 54.6%, a saving of about 6,200 GWh (92,822 rather than 99,065 GWh) could be achieved to satisfy the production $P_{CC\_2012}$. This corresponds to a percentage reduction of 6.3% with respect to the actual consumption to a 51.1% efficiency.

Obviously, the operating management of CC plants indicated above, even if satisfying the global energy demand of 2012, probably does not meet the constraints relative to the thermoelectric plants location on the electric grid. In fact, it implies a definitive shut-off of CC plants corresponding to about 60% of power actually operated in 2012 (25,408 MW). Due to the elongated shape of the Italian territory and the consequent structure of the national electric grid, a suitable number of power plants must be kept on operation for balance of grid sections.

For those reasons, it is necessary to introduce ESS to allow a postponed usage of the produced energy. ESS integration implies an energy cost, which increases with the energy rate to be stored in comparison with the annual total production and depends also on the efficiency of the considered storage technology. Therefore, the additional energy consumption, necessary for ESS integration, was calculated through a sensitive analysis by varying energy rate to be stored and ESS efficiency. Main storage technologies are included, i.e. CAES (70% efficiency [31]), PSH and enhanced PSH (70-85% efficiency [2], [31]) and ESB (energy storage battery with 90-95% efficiency [31]).

With reference to Table 4, which summarizes the results of this analysis, all the cases (highlighted in grey) with an additional consumption lower than 6,200 GWh, corresponding to the energy saving due to the CC high-efficiency operation, are of interest. Clearly, by increasing the ESS efficiency, the amount of energy, which can be conveniently stored, also grows.

**Table 4 Energy consumed for energy storage**

The implementation of the ESS penetration scenario of Table 4 needs of a suitable management strategy of the CC plants. To investigate the proper strategy and the impact of ESS integration in terms of energy saving, in the following, a particular case is considered as example.

Specifically, ESS capacity corresponding to 30% of $P_{CC\_2012}$ (15,196 GWh) and ESS efficiencies of 85% were assumed. The latter value is compatible with the use of ESB technologies, being below their efficiency values [2], [36], [31]. Furthermore, in relation to the PSH systems, which currently constitute nearly all of the existing storage facilities, the considered performance value corresponds to the upper efficiency bound characteristic of the current technology as indicated in [2], [36]. In relation also to the improvements expected in the short and medium term [2], as indicated in the Technology Map of the European SET-Plan [31] mainly regarding the use of generation equipment with improved efficiency, this value can be considered plausible for possible future applications.

Taking into account the storage efficiencies indicated above, the surplus of electric energy needed by ESS operation was evaluated in 2,682 GWh (5.3% of $P_{cc\_2012}$). This value corresponds to an overall production ($P_{cc}$) of 53,334 GWh vs. 50,652 GWh actually produced in 2012 by CC.

In order to guarantee the $P_{cc}$ data indicated above with a CC plants efficiency of 54.6%, the proposed operation strategy implies the shutoff of 43.8% thermoelectric plants, in terms of current capacity. In particular, the ESS penetration, in the measure indicated above, allows to have 14,280 MW working for 3,547 $H_{eq}$ under 54.6% efficiency, instead of 9,996 MW with an operation time of 5,067 $H_{eq}$ calculated without ESS. In fact, 30% of stored energy ($E_{st}$) with respect to $P_{cc\_2012}$ is determined as (Eq.3):

$$E_{st} = \frac{[14{,}280(MW) - 9{,}996(MW)] \cdot 3{,}547(h)}{P_{CC_{2012}}(MWh)} \tag{3}$$

Therefore, ESSs allow to have a larger number of CC plants in operation (equal to about 56% of the installed power) at a higher efficiency (54.6%) with a smaller $H_{eq}$ (as evident in Figure 14 which depicts the $H_{eq}$ – efficiency correlation characteristic of CC plants working without ESS), ensuring the same total production (increment of 5.3%). This allows a greater flexibility relative to both actual demand profile and thermoelectric plants location with respect to the territorial grid layout.

The primary energy saving characteristic of the investigated case can be assessed through the determination of the CC energy input, as $P_{cc}$/54.6%, and the calculation of the gap with respect to the 99,065 GWh consumed in 2012 under actual operation conditions. This procedure results in a primary energy saving of 1,329 GWh for the particular case considered as example. It corresponds to an annual saving of $138 \cdot 10^6$ $Sm^3$ of natural gas, rather than about 100 M€/year and 84 M€/year, considering for the natural gas the mean National Single Price PUN value of 2012 (75.48 €/MWh) and 2013 (62.99 €/MWh) respectively [27].

Moreover, it is important to quantify the avoided wear-and-tear costs due to cycling operation. As shown in [36], these costs for the average fossil-fuelled plant could be quantified in € 0.36 to € 1 per MWh of fossil-fuelled generation. Therefore, considering the entire annual production of $P_{cc\_2012}$, a further saving of about 18.5 to 50.2 M€/year can be reached by adopting the ESS-CC solution.

The presented analysis was focused on one possible example to evaluate, relative to the Italian thermoelectric sector, the gross effect of ESS-CC coupling. It has not to be considered as a full economic study of the ESS-CC solution, since it addresses only the evaluation of energetic and economic advantages related to a more performant CC operation in terms of both efficiency and wear-and-tear damage. Obviously, additional and more accurate analysis are needed to evaluate the actual feasibility of this strategy.

# 4 Conclusions

This paper addresses the impact of renewable sources on the Italian thermoelectric sector. This scenario is characterized by a quick and significant RES growth without a suitable regulatory framework contributing to ESS integration in the national energy system.

In particular, the drop in thermoelectric efficiency occurred in Italy in the period 2008-2012 is deeply analyzed, quantified and related to the RES growth in the same period. Specifically, in the absence of a regulatory framework concerning ESS integration and under a contextual trend of the energetic commodities bringing to a greater use of lower quality fuels (i.e. coal), a decrease in the thermoelectric generation efficiency, mainly due to CC operation management, is observed.

This performance degradation is evaluated, with respect to a reference operation modality (54.6% yearly mean efficiency), in about 6,200 GWh of energy penalty with reference to the energy production of CC plants in 2012. This consumption penalty corresponds to the 6.3% of the corresponding natural gas consumption.

To mitigate this inefficiency, the integration of ESS is preliminarily investigated aiming to operate CC plants in conditions (reference operation modality as indicated above) closer to the nominal ones and avoiding their functioning as backup power of RES plants.

Therefore, pointing on the strategy of integrating storage technology with the operation of thermoelectric plants and, specifically, reviewing the CC operating conditions, the impact of possible ESS coupling with CC plants is quantified through a sensitivity analysis. The percentage of the yearly stored energy and the ESS efficiency are considered as the variation parameters. Among all the resulting solutions, a possible scenario is analyzed, corresponding to a 30% rate of stored energy with respect to $P_{CC\_2012}$ and 85% of ESS efficiency value.

The need to shut-down part of CC installed power (about 44%), depending on the produced energy rate (30%) to be stored, is demonstrated to guarantee CC plants working as long as possible at nominal operating conditions. Under these assumptions and in order to satisfy the $P_{CC\_2012}$ production, energy savings of about 1.5% of the CC plants consumption in 2012 are obtained. Another advantage is the reduction on wear-and-tear damage. Considering that the amount of wear-and-tear costs due to plant cycling are valued in the range 0.36-1 €/MWh, about 18.5 to 50.2 M€/year can be saved relative to O&M costs additionally to about 100 M€/year due to the energy saving indicated above.

These assessments, carried out with a simplified analysis for a particular example case, can be further improved at a national level and expanded at an international level, but they are strongly affected by the expected improvements of ESS technologies mainly relative to the reduction in their capital cost. What this study clearly showed is that further introduction of either programmable or unprogrammable RES requires a strong strategic decision on investing in ESS, to avoid operating large CCs at lower efficiency and increasing the use of coal instead of natural gas.

Also improvements of the regulatory framework are strongly expected contributing to perspectives of profitable storage operation. In this framework, a first regulation could impose the installation of an ESS for each new large scale unprogrammable renewable power plant.

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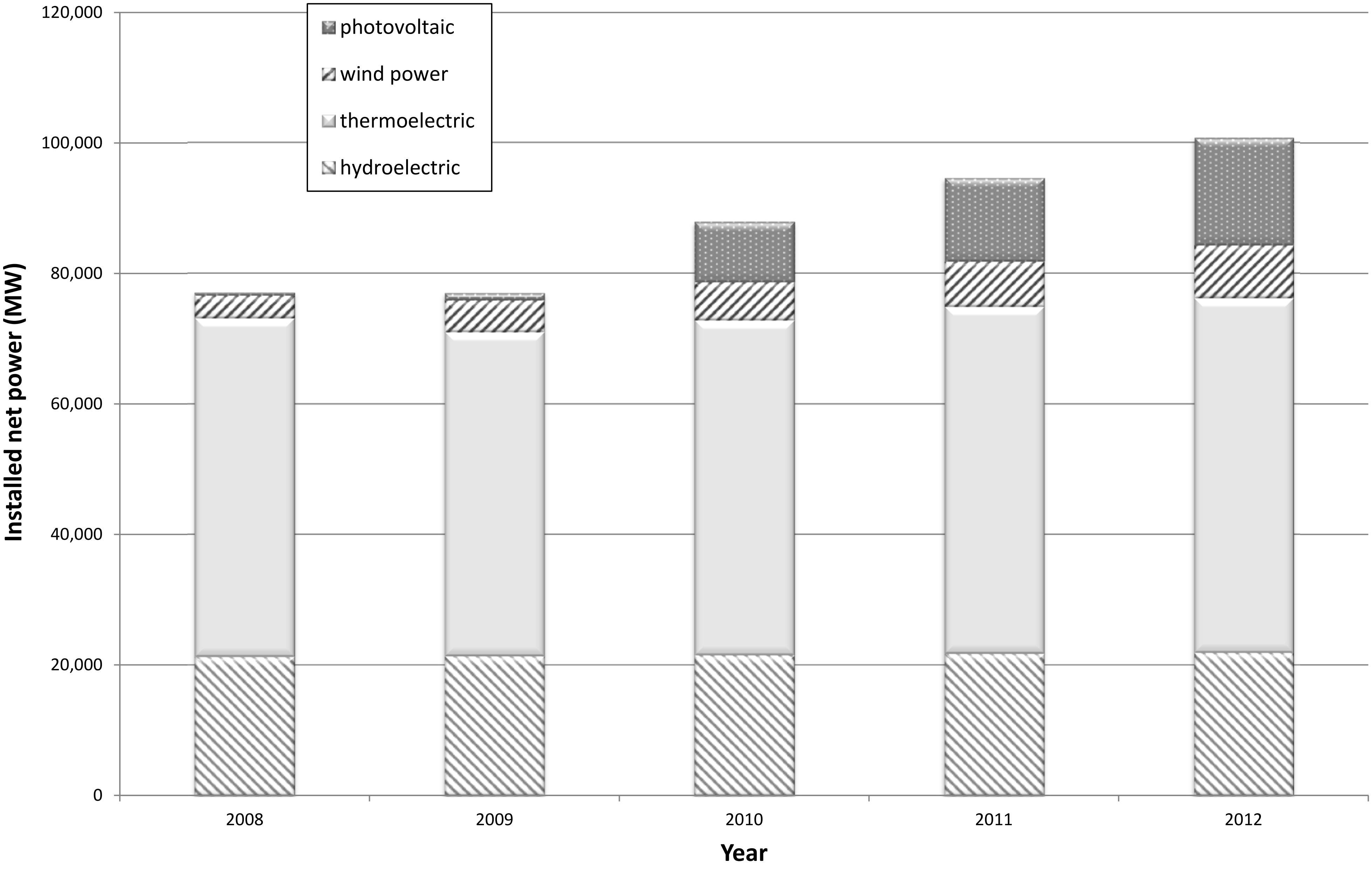
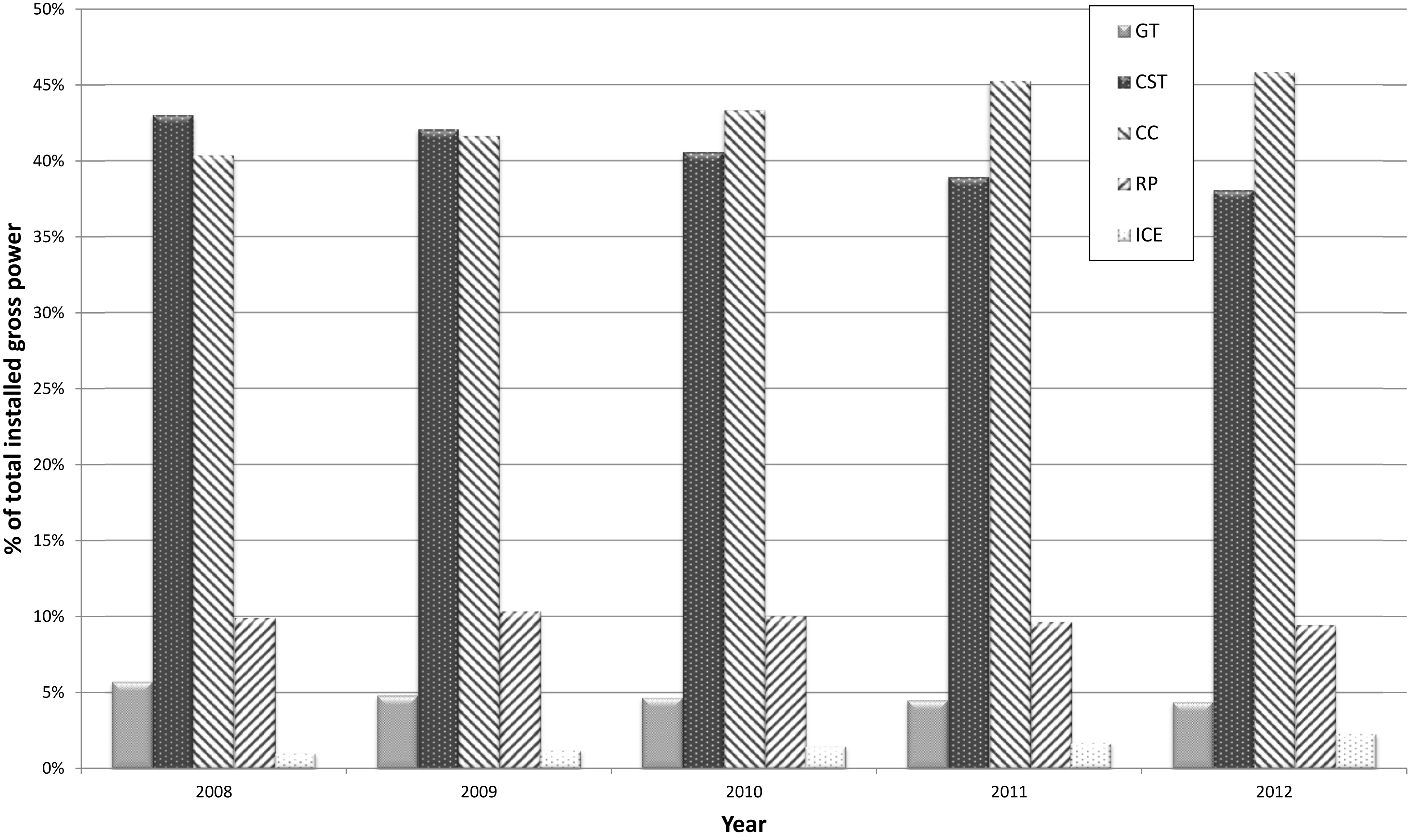


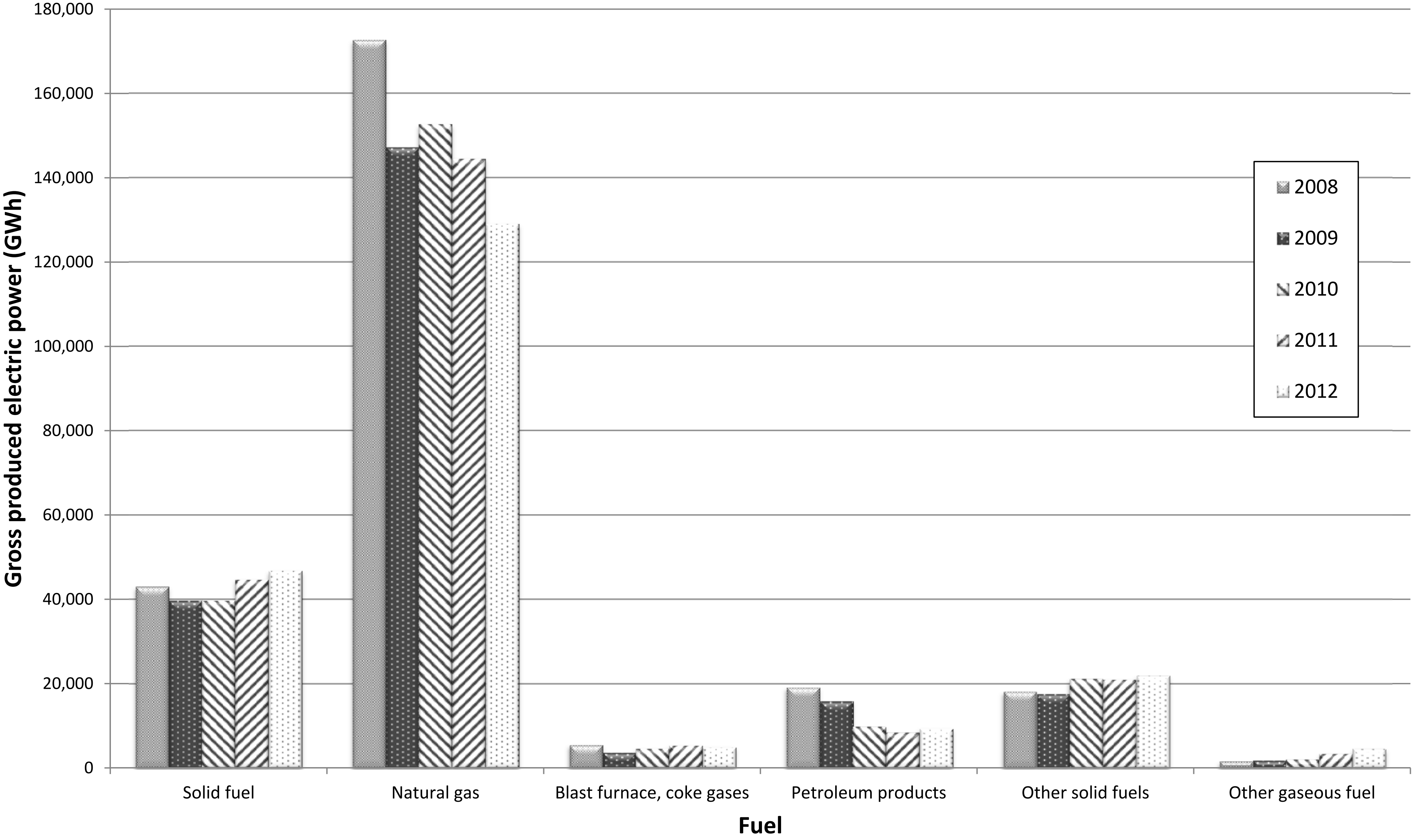
photovoltaic
wind power
thermoelectric
hydroelectric
120,000
100,000
80,000
60,000
40,000
20,000
0
Installed net power (MW)
2008
2009
2010
2011
2012
Year

**Figure 2**



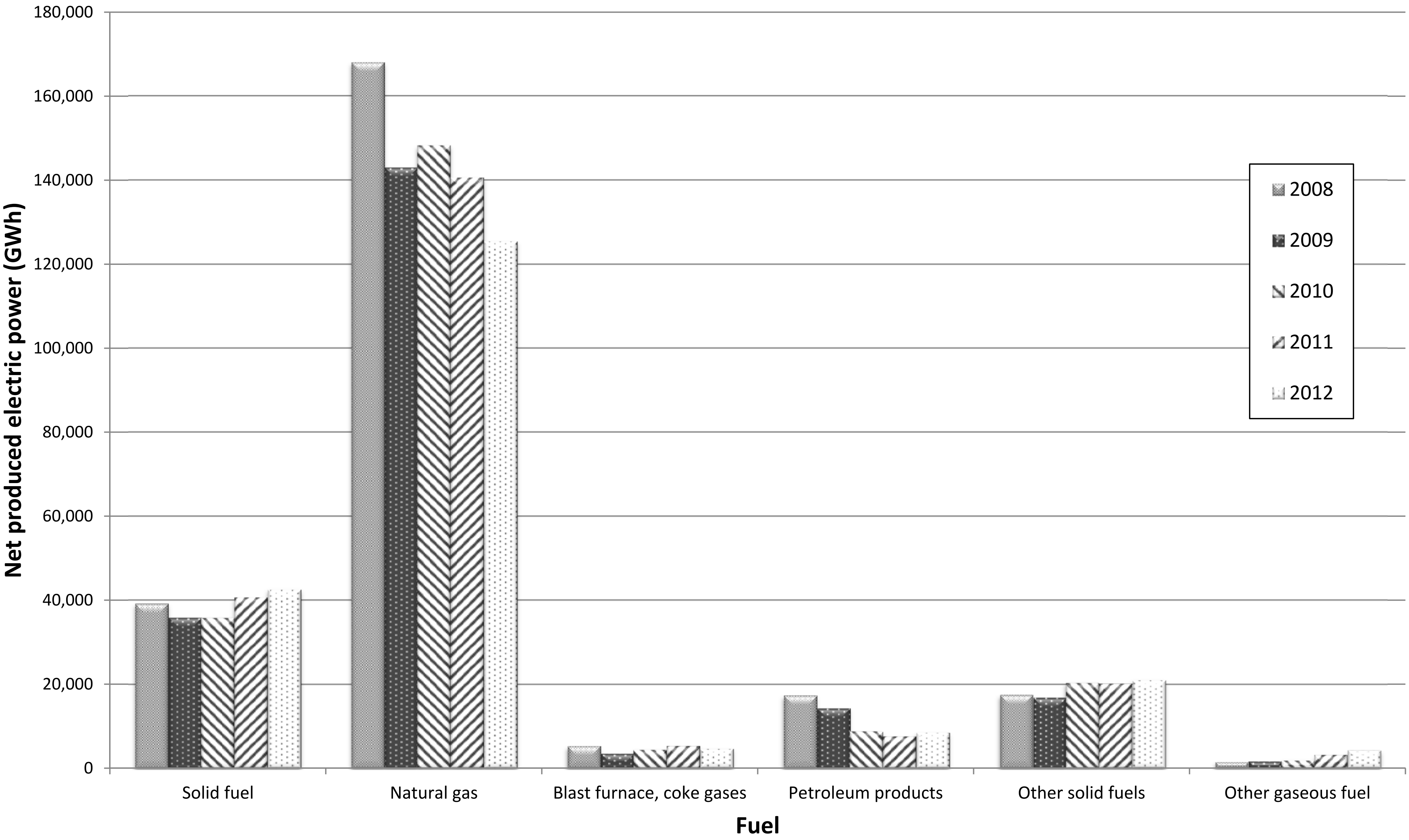
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
% of total installed gross power
2008
2009
2010
2011
2012
Year
GT
CST
CC
RP
ICE

Figure 3



Gross produced electric power (GWh)
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
Solid fuel
Natural gas
Blast furnace, coke gases
Petroleum products
Other solid fuels
Other gaseous fuel
Fuel
2008
2009
2010
2011
2012

Figure 4



Net produced electric power (GWh)
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
Solid fuel
Natural gas
Blast furnace, coke gases
Petroleum products
Other solid fuels
Other gaseous fuel
Fuel
2008
2009
2010
2011
2012

**Figure 5**

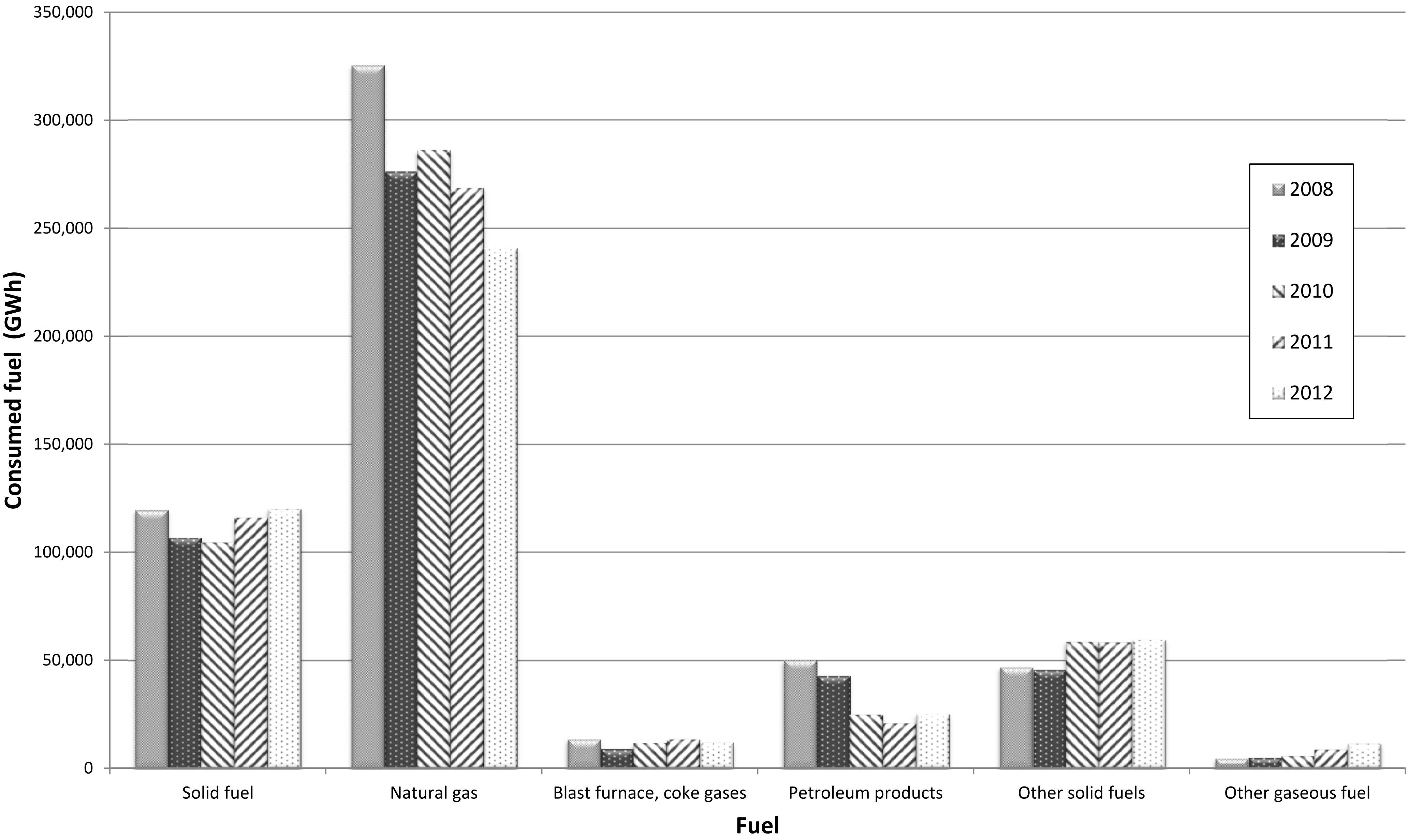

350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
Consumed fuel (GWh)
Solid fuel
Natural gas
Blast furnace, coke gases
Petroleum products
Other solid fuels
Other gaseous fuel
Fuel
2008
2009
2010
2011
2012

Figure 6

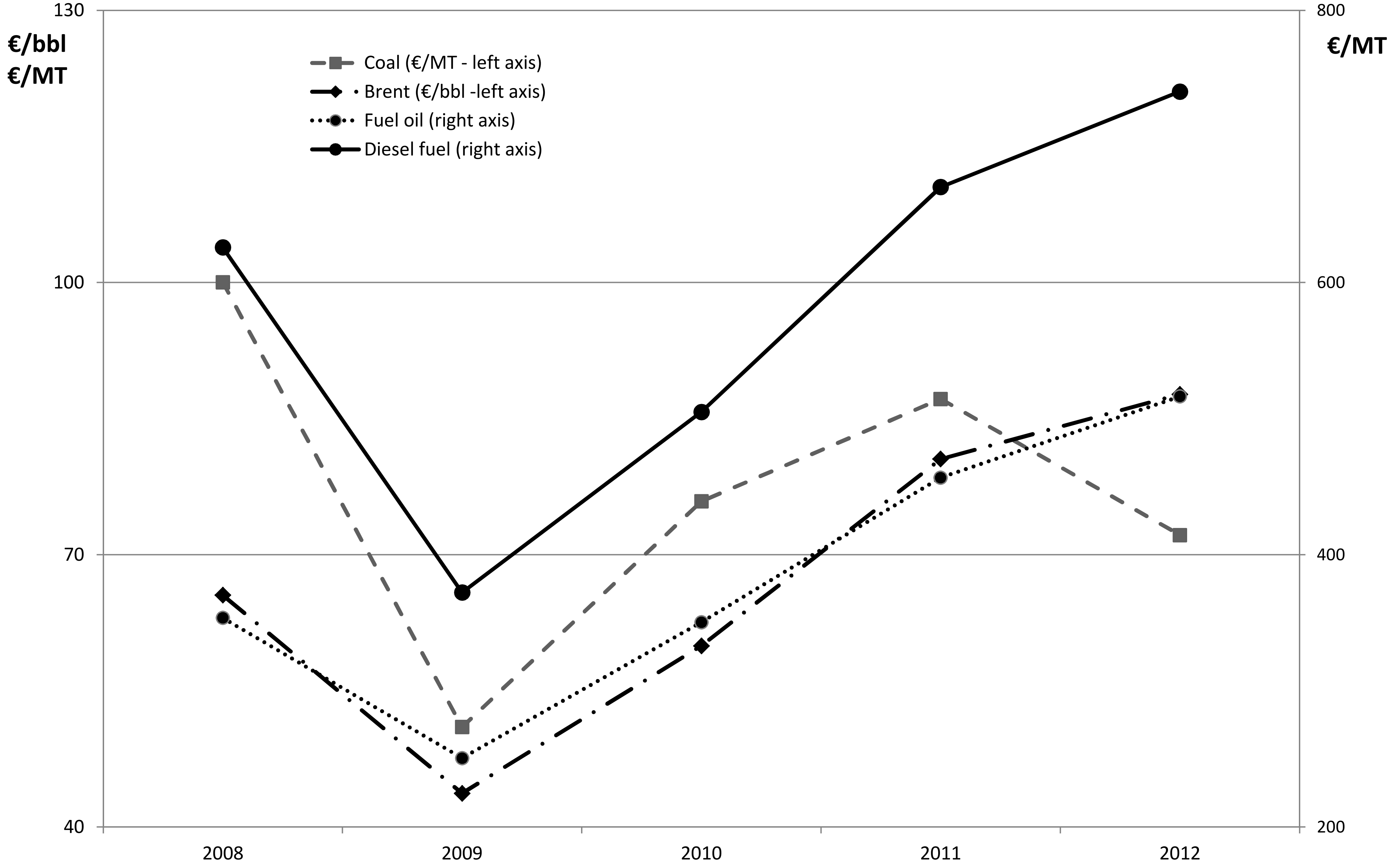

€/bbl
€/MT
€/MT
Coal (€/MT - left axis)
Brent (€/bbl -left axis)
Fuel oil (right axis)
Diesel fuel (right axis)
130
100
70
40
800
600
400
200
2008
2009
2010
2011
2012

**Figure 7**

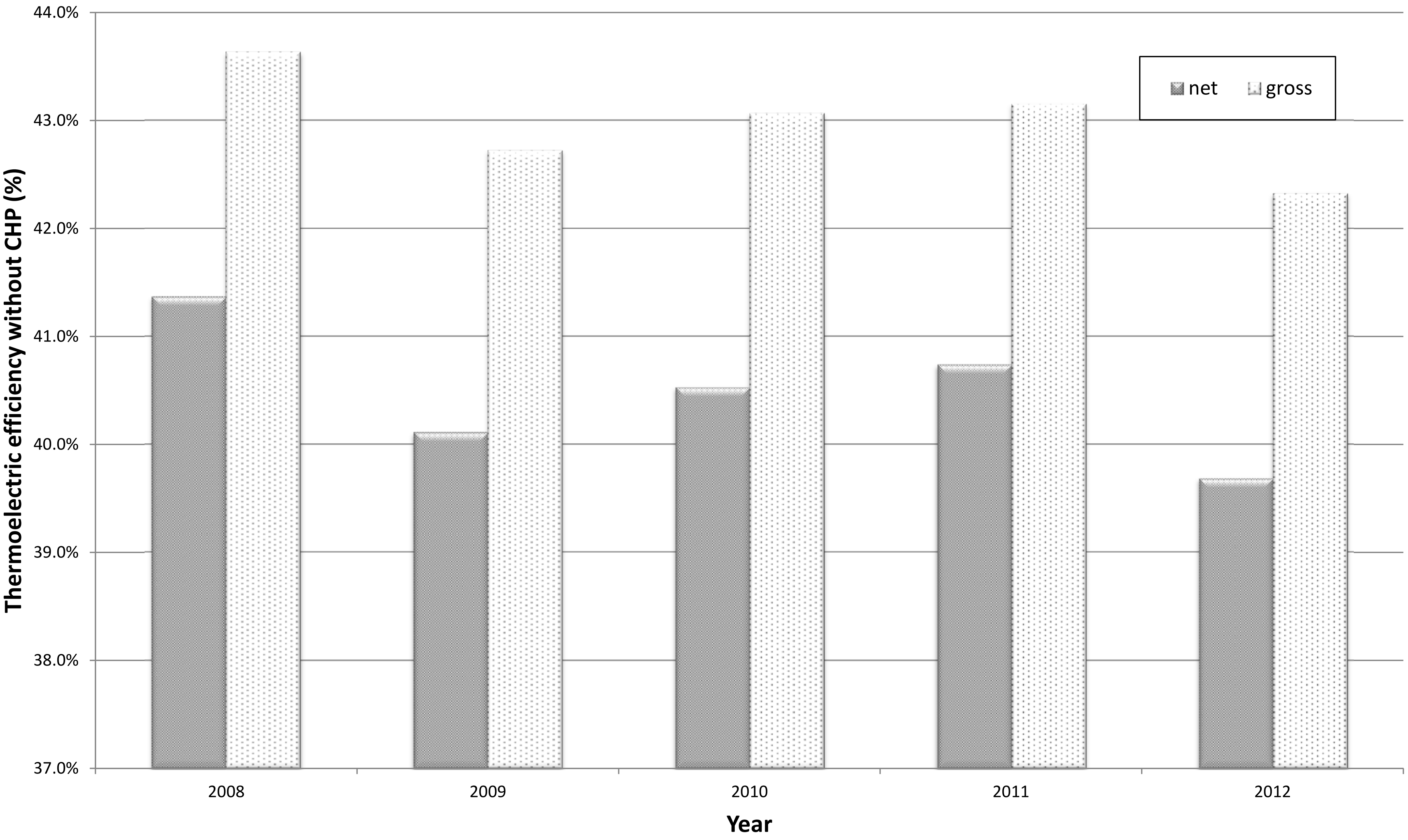

44.0%
43.0%
42.0%
41.0%
40.0%
39.0%
38.0%
37.0%
Thermoelectric efficiency without CHP (%)
net
gross
2008
2009
2010
2011
2012
Year

**Figure 8**

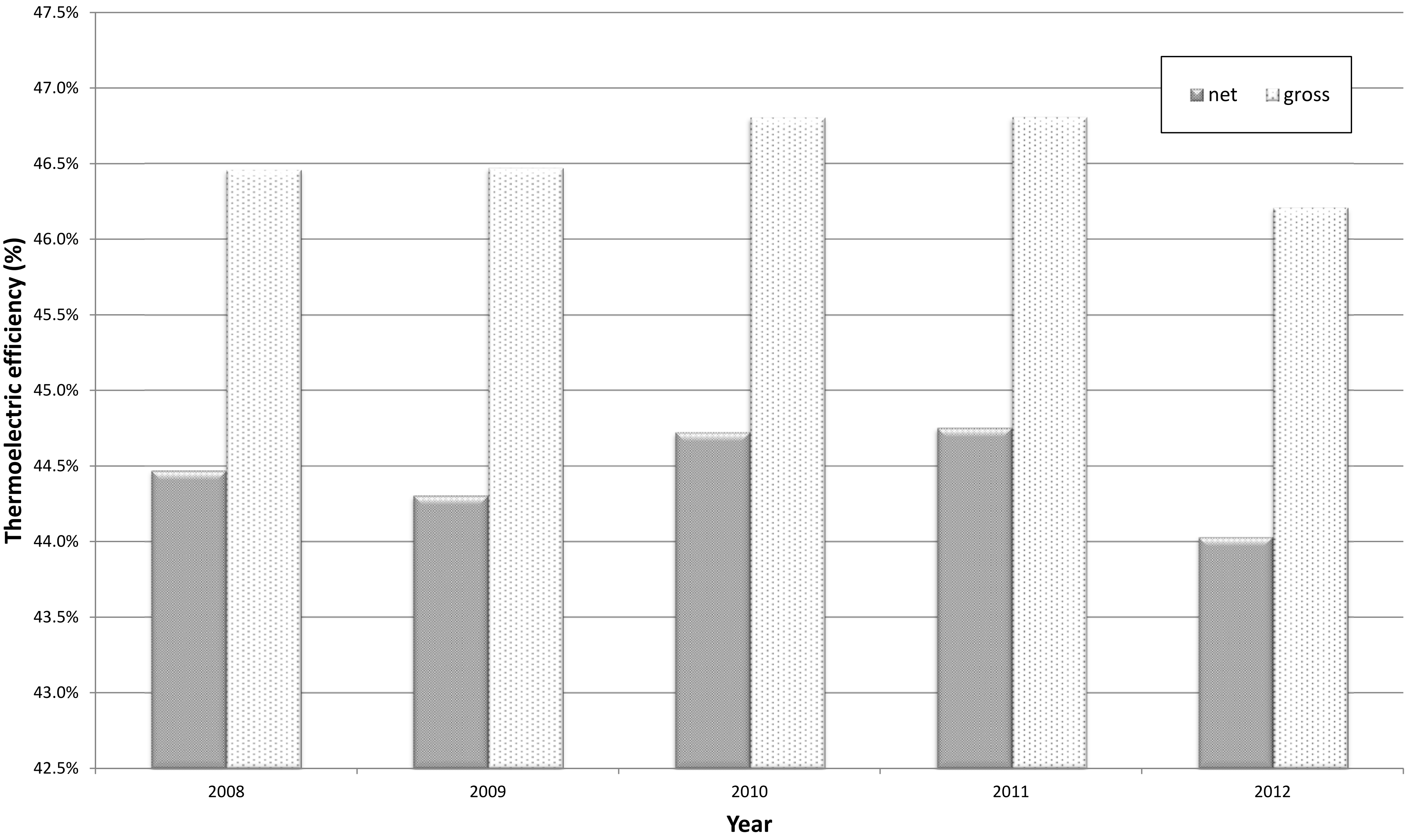

47.5%
47.0%
46.5%
46.0%
45.5%
45.0%
44.5%
44.0%
43.5%
43.0%
42.5%
Thermoelectric efficiency (%)
net
gross
2008
2009
2010
2011
2012
Year

Figure 9

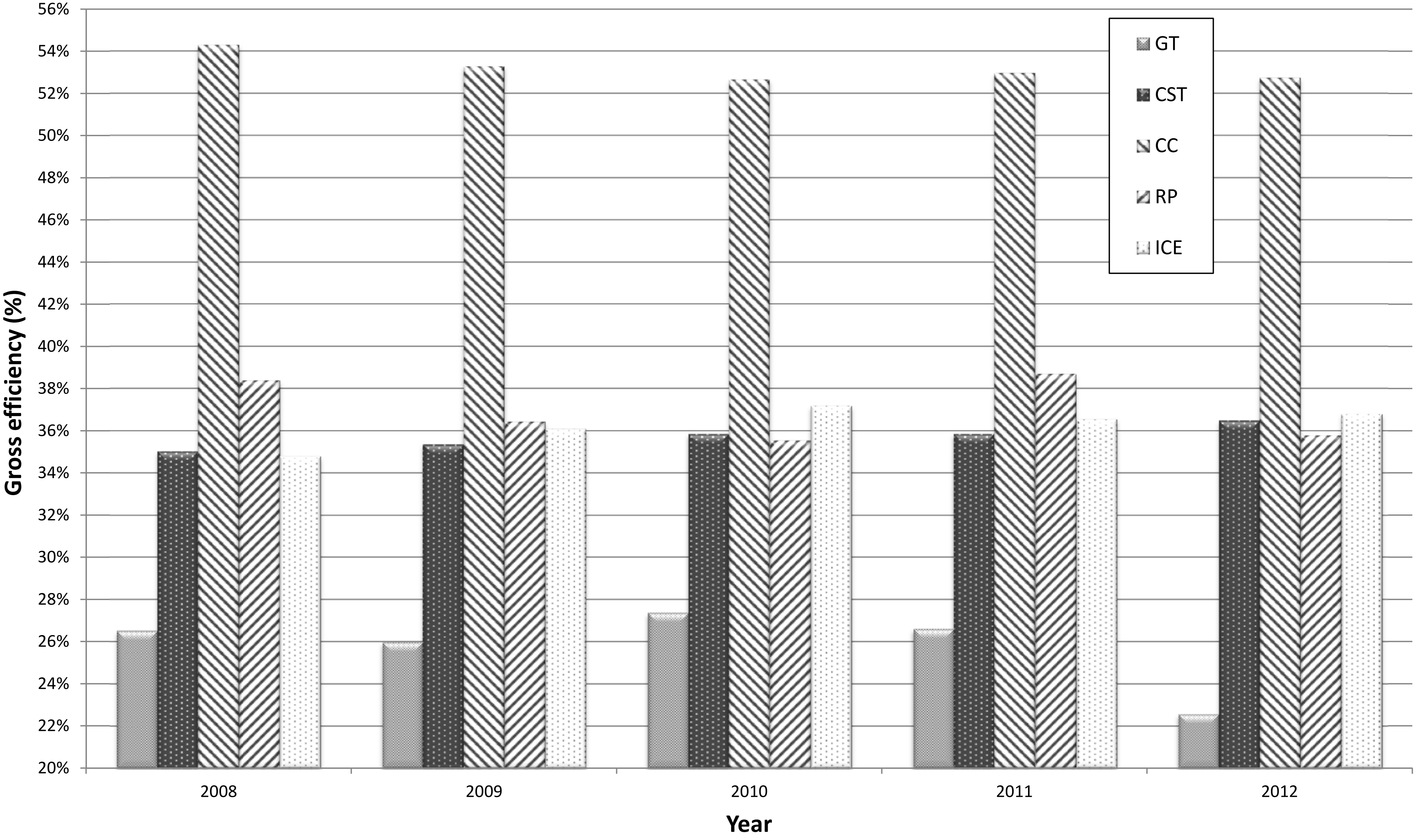
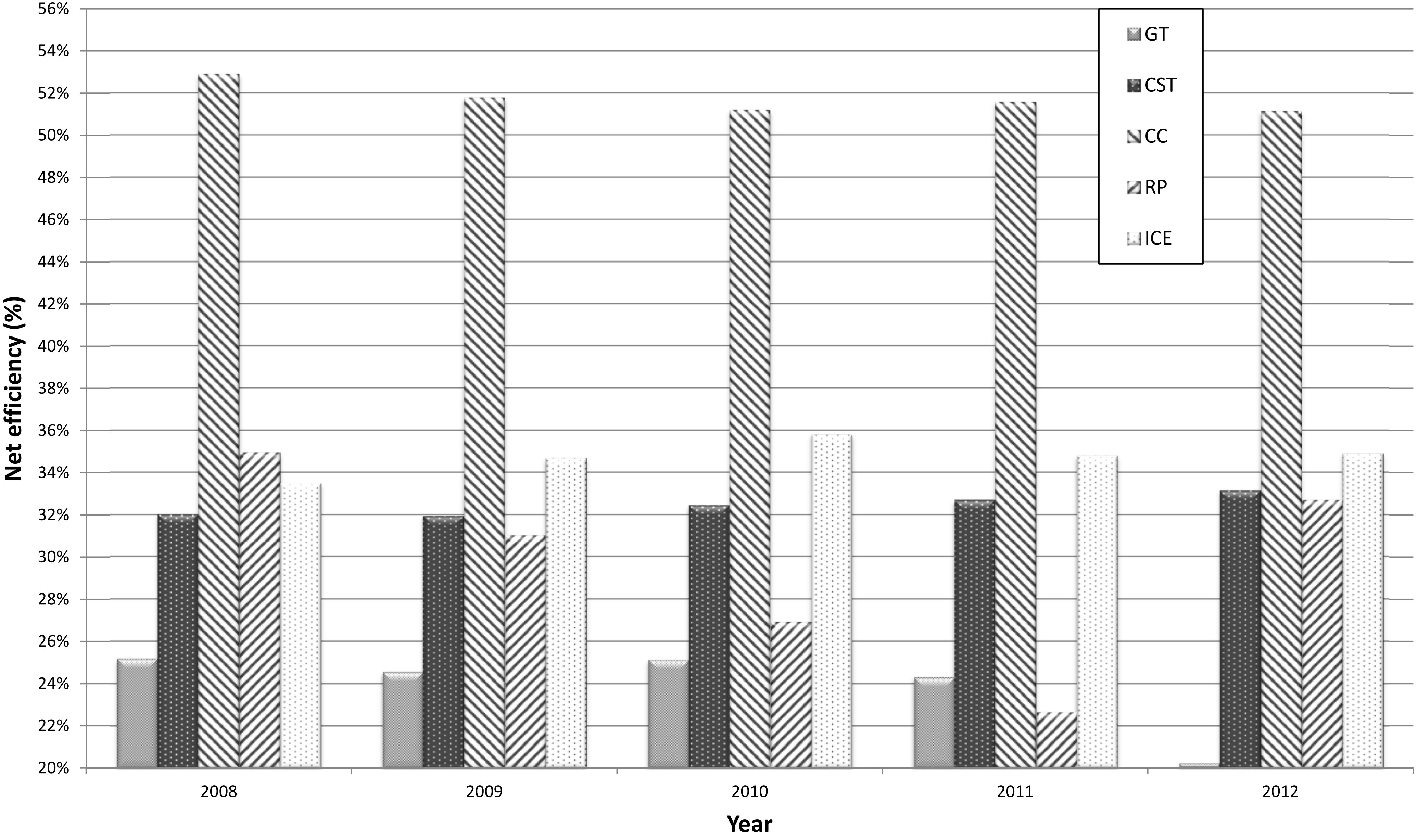
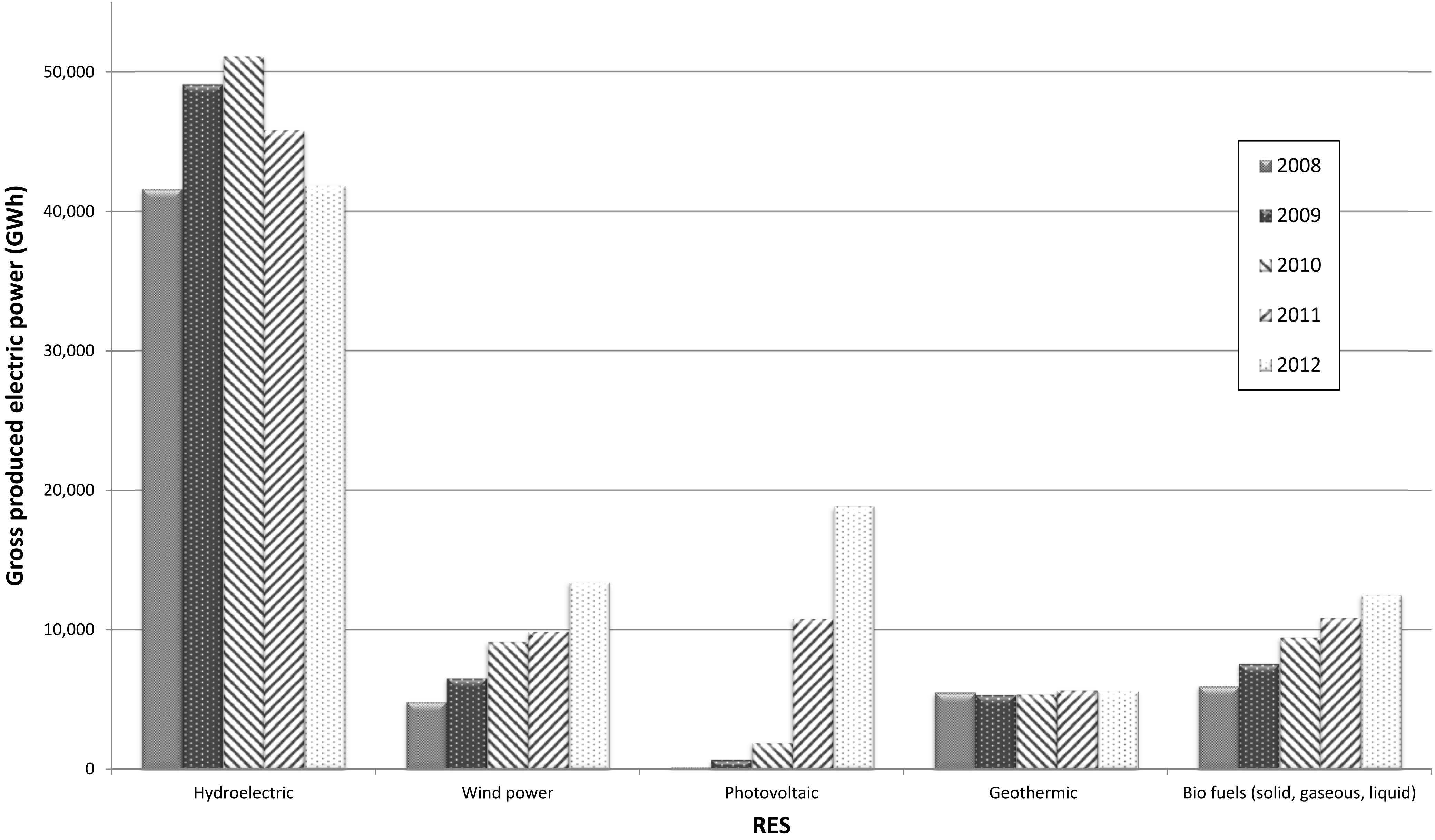

56%
54%
52%
50%
48%
46%
44%
42%
40%
38%
36%
34%
32%
30%
28%
26%
24%
22%
20%
Gross efficiency (%)
2008
2009
2010
2011
2012
Year
GT
CST
CC
RP
ICE

**Figure 10**



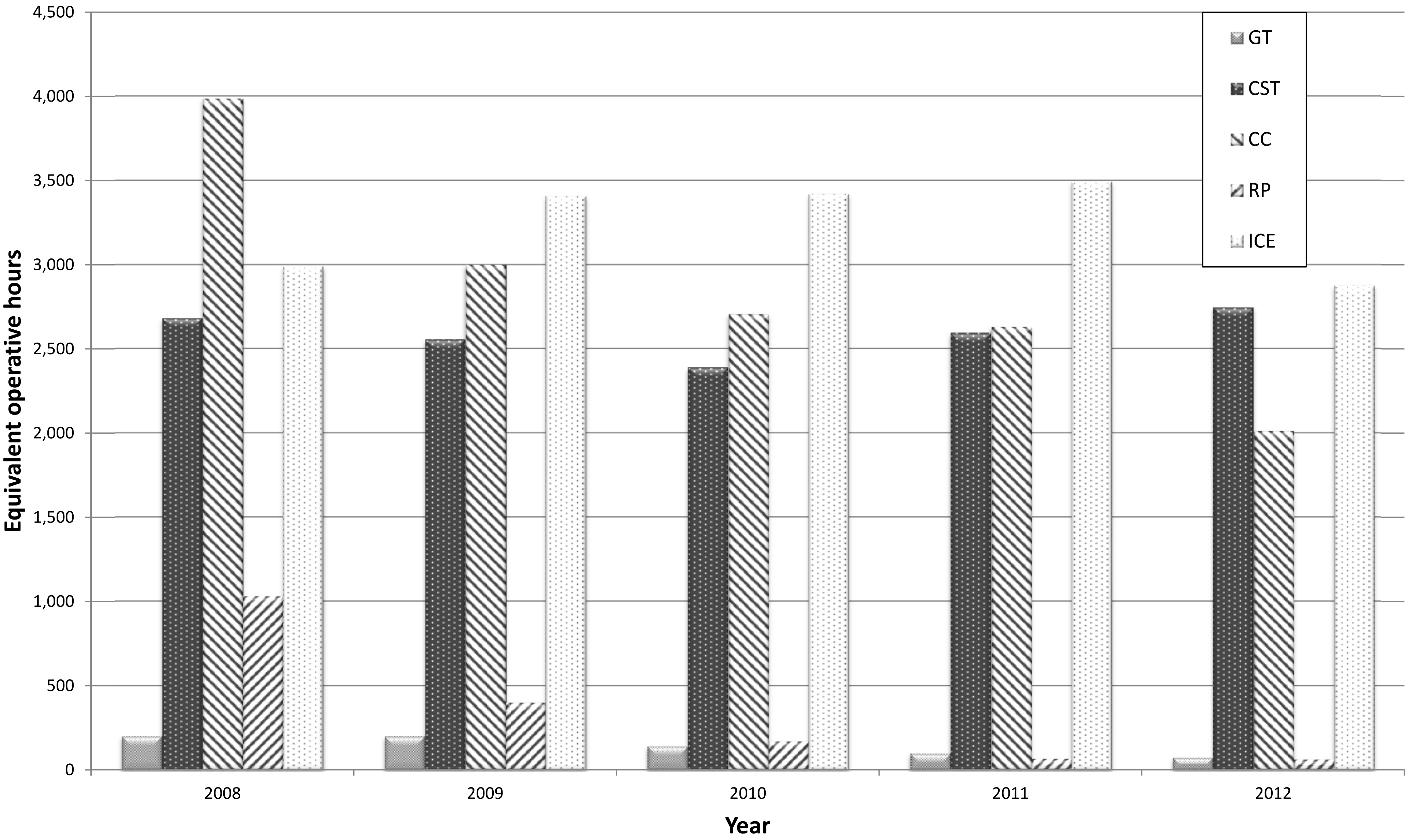
56%
54%
52%
50%
48%
46%
44%
42%
40%
38%
36%
34%
32%
30%
28%
26%
24%
22%
20%
Net efficiency (%)
2008
2009
2010
2011
2012
Year
GT
CST
CC
RP
ICE

Figure 11



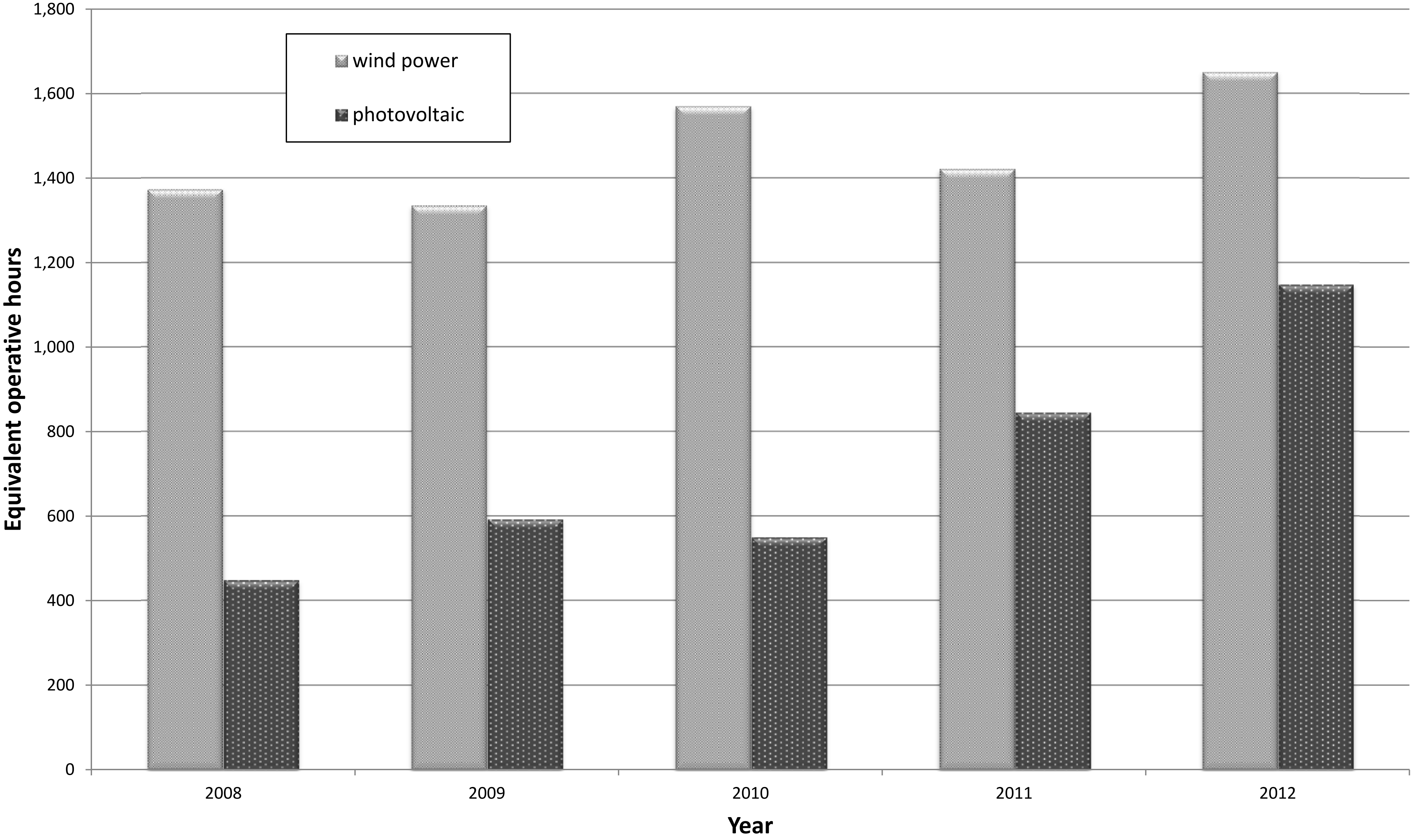
Gross produced electric power (GWh)
50,000
40,000
30,000
20,000
10,000
0
2008
2009
2010
2011
2012
Hydroelectric
Wind power
Photovoltaic
Geothermic
Bio fuels (solid, gaseous, liquid)
RES

Figure 12



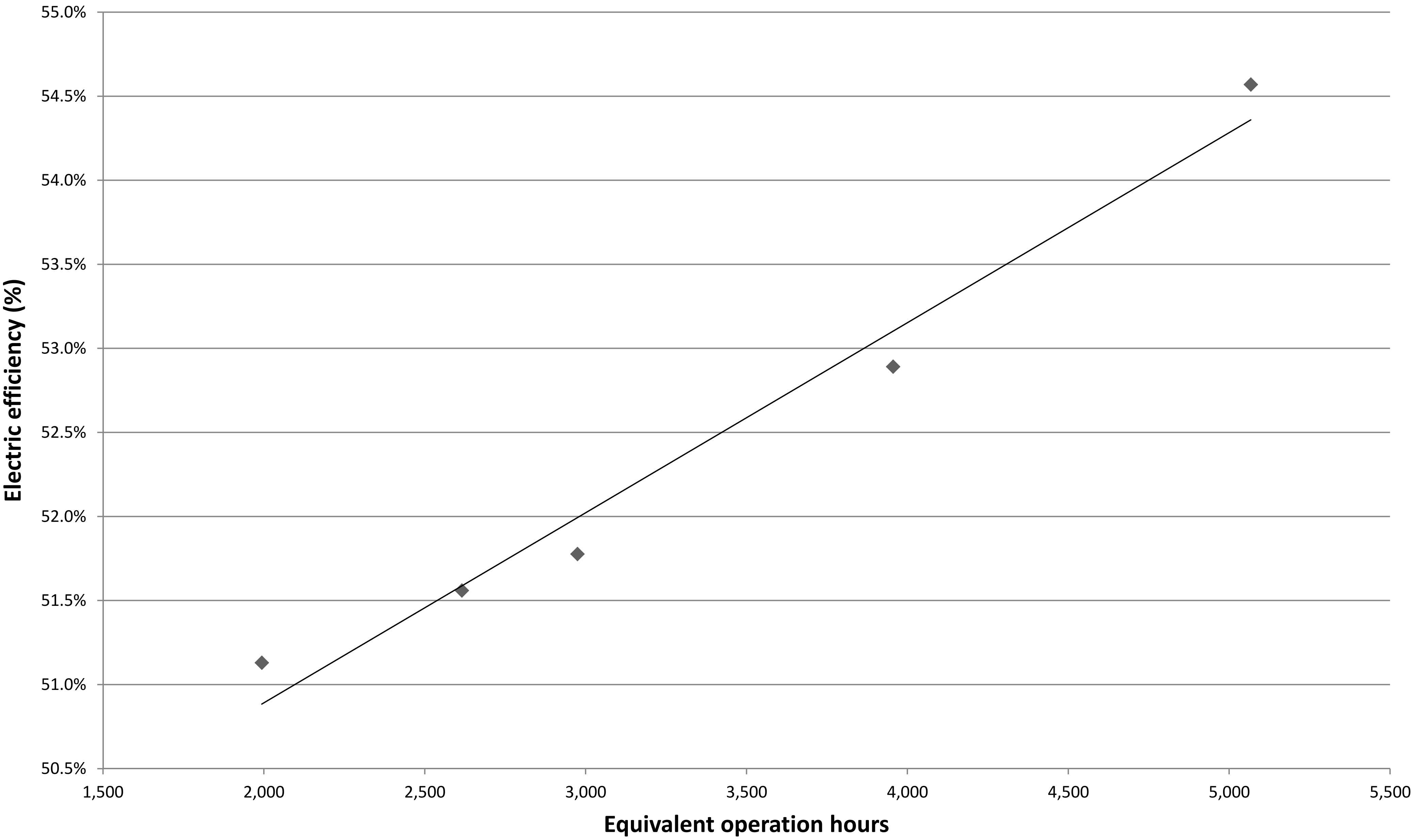
Equivalent operative hours
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
2008
2009
2010
2011
2012
Year
GT
CST
CC
RP
ICE

Figure 13



wind power
photovoltaic
Equivalent operative hours
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
2008
2009
2010
2011
2012
Year

**Figure 14**


55.0%
54.5%
54.0%
53.5%
53.0%
52.5%
52.0%
51.5%
51.0%
50.5%
Electric efficiency (%)
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
5,500
Equivalent operation hours

# Table

| | Gross production (GWh) | | | | | Net production (GWh) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Power plant typology** | **2008** | **2009** | **2010** | **2011** | **2012** | **2008** | **2009** | **2010** | **2011** | **2012** |
| **ICE** | 1,886 | 2,463 | 3,047 | 3,674 | 3,996 | 1,815 | 2,366 | 2,935 | 3,499 | 3,792 |
| **GT** | 622 | 501 | 357 | 253 | 192 | 591 | 473 | 328 | 231 | 172 |
| **CST** | 62,713 | 55,953 | 52,119 | 55,920 | 59,230 | 57,335 | 50,573 | 47,189 | 50,984 | 53,809 |
| **CC** | 86,795 | 64,558 | 62,568 | 65,985 | 52,214 | 84,567 | 62,717 | 60,839 | 64,239 | 50,652 |
| **RP** | 5,471 | 2122 | 912 | 360 | 340 | 4,980 | 1,807 | 691 | 211 | 311 |
| **Total thermoelectric without CHP** | 157,487 | 125,596 | 119,003 | 126,192 | 115,972 | 149,288 | 117,936 | 111,980 | 119,163 | 108,735 |

**Table 1 Energy production for each power plant technology**

| | Equivalent operation hours ($H_{eq}$) | | | | | Installed power in 2012 (MW) | % of total installed power in 2012 |
|---|---|---|---|---|---|---|---|
| | **2008** | **2009** | **2010** | **2011** | **2012** | | |
| **ICE** | 2,993 | 3,408 | 3,421 | 3,494 | 2,879 | 1,289 | 2% |
| **GT** | 201 | 200 | 142 | 99 | 75 | 2,477 | 4% |
| **CST** | 2,685 | 2,557 | 2,391 | 2,594 | 2,748 | 21,539 | 38% |
| **CC** | 3,987 | 3,002 | 2,708 | 2,633 | 2,013 | 25,934 | 46% |
| **RP** | 1,029 | 399 | 171 | 68 | 64 | 5,318 | 9% |

**Table 2 $H_{eq}$ calculated on the basis of gross production and installed power data**

| | CC - only electricity production | | | | | CC - CHP |
|---|---|---|---|---|---|---|
| **Year** | *2008* | *2009* | *2010* | *2011* | *2012* | *2012* |
| **Net Production (GWh)** | 84,567 | 62,717 | 60,839 | 64,239 | 50,652 | 80,490 |
| **Equivalent operation hours** | 3,956 | 2,975 | 2,685 | 2,615 | 1,994 | 5,067 |
| **Efficiency refers to net production** | 52.9% | 51.8% | 51.2% | 51.6% | 51.1% | 54.6% |
| **Primary energy used (GWh)** | 159,889 | 121,129 | 118,846 | 124,592 | 99,065 | 147,501 |
| **Mean delivered power to satisfy electric production in 2012 (MW)** [a] | 12,805 | 17,027 | 18,866 | 19,366 | 25,408 | 15,884 |
| **Hours ratio** [b] | 78% | 59% | 53% | 52% | 39% | 100% |

[a] ratio between electric production in 2012 and CC equivalent operative hours of each year

[b] ratio between Heq of CC and CC-CHP plants

**Table 3 CC and CC-CHP plants performance comparison**

| **Energy to storage system (GWh)** | 1,013 | 2,026 | 3,039 | 4,052 | 5,065 | 6,078 | 7,091 | 8,104 | 9,117 | 10,130 | 11,143 | 12,157 | 13,170 | 14,183 | 15,196 | 16,209 | 17,222 | 18,235 | 19,248 | 20,261 | 21,274 | 22,287 | 23,300 | 24,313 | 25,326 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **% of net 2012 production** | 2% | 4% | 6% | 8% | 10% | 12% | 14% | 16% | 18% | 20% | 22% | 24% | 26% | 28% | 30% | 32% | 34% | 36% | 38% | 40% | 42% | 44% | 46% | 48% | 50% |
| **ESS efficiency** | **Primary energy consumed for energy storage** | | | | | | | | | | | | | | | | | | | | | | | | |
| 70% | 796 | 1,591 | 2,387 | 3,182 | 3,978 | 4,774 | 5,569 | 6,365 | 7,161 | 7,956 | 8,752 | 9,547 | 10,343 | 11,139 | 11,934 | 12,730 | 13,526 | 14,321 | 15,117 | 15,912 | 16,708 | 17,504 | 18,299 | 19,095 | 19,890 |
| 75% | 619 | 1,238 | 1,856 | 2,475 | 3,094 | 3,713 | 4,332 | 4,951 | 5,569 | 6,188 | 6,807 | 7,426 | 8,045 | 8,663 | 9,282 | 9,901 | 10,520 | 11,139 | 11,757 | 12,376 | 12,995 | 13,614 | 14,233 | 14,852 | 15,470 |
| 80% | 464 | 928 | 1,392 | 1,856 | 2,321 | 2,785 | 3,249 | 3,713 | 4,177 | 4,641 | 5,105 | 5,569 | 6,033 | 6,498 | 6,962 | 7,426 | 7,890 | 8,354 | 8,818 | 9,282 | 9,746 | 10,210 | 10,675 | 11,139 | 11,603 |
| 85% | 328 | 655 | 983 | 1,310 | 1,638 | 1,966 | 2,293 | 2,621 | 2,948 | 3,276 | 3,604 | 3,931 | 4,259 | 4,587 | 4,914 | 5,242 | 5,569 | 5,897 | 6,225 | 6,552 | 6,880 | 7,207 | 7,535 | 7,863 | 8,190 |
| 90% | 206 | 413 | 619 | 825 | 1,031 | 1,238 | 1,444 | 1,650 | 1,856 | 2,063 | 2,269 | 2,475 | 2,682 | 2,888 | 3,094 | 3,300 | 3,507 | 3,713 | 3,919 | 4,125 | 4,332 | 4,538 | 4,744 | 4,951 | 5,157 |
| 95% | 98 | 195 | 293 | 391 | 489 | 586 | 684 | 782 | 879 | 977 | 1,075 | 1,172 | 1,270 | 1,368 | 1,466 | 1,563 | 1,661 | 1,759 | 1,856 | 1,954 | 2,052 | 2,150 | 2,247 | 2,345 | 2,443 |

Table 4 Energy consumed for energy storage