Analysis of the influence of Power-to-Gas systems in cyclic performance of fossil fuel power plants

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Abstract:

The increase of the renewable share in the energy generation mix results in higher uncertainties in the operational predictability and flexibility of the electricity market. This fluctuating surplus power affects the performance of the fossil fuel thermal power plants (FFPP) that will have to adapt their electricity production to compensate these changes. This load reduction implies a significant energetic penalty caused by a loss of efficiency of the thermal power plants operating at partial loads and, consequently, the increase of specific CO2 emissions. Energy storage technologies have been proposed to overcome the problems caused by renewable resources fluctuations. In particular, Power to Gas (PtG) allows for the storage of excess of electrical energy in form of synthetic natural gas (SNG) through the methanation of hydrogen produced by electrolysis. When CO2 capture systems (CCS) are involved to provide the concentrated stream of CO2 required in PtG process, the recycle of CO2 avoids additional carbon emissions. In this work, the loss of efficiency and the specific CO2 emissions in FFPP have been quantified under different loads simulating the effect of load variation due to renewable energy penetration into the grid. It is proposed the integration of a PtG system to reduce the lower limit of FFPP load before shut-downs. This integration strategy will allow keeping in operation power plants during periods with low demand and it will also avoid the cost of shut-down and start-up. The surplus power will be sent to an electrolyser to produce SNG after methanation reaction. Results show and quantify the additional benefits of PtG system as an economical solution to avoid shut-downs and hot/warm and cold starts in power plants. Moreover, an additional production of SNG could be stored and used taking advantage of extra incomes and reducing costs.

Keywords:
Energy storage, fossil fuel power plants, CO_2 emissions, electricity market.

1. Introduction

The share of energy produced from renewable resources (RES, Solar, Wind, Hydro, Biomass) is growing rapidly, according to the “EU Reference Scenario 2016. Energy, transport and GHG emissions. Trends to 2050” [1] RES will produce 44% of net electricity generation by 2030 and 56% in 2050. Given the intrinsic limitations to growth of conventional RES (Hydro and Biomass), the integration in the generation mix of variable renewable electricity (VRE), mainly solar and wind power, has become a priority for many regions in the world in order to achieve a low-carbon sustainable economy, which carries along clear environmental, social and economic benefits. However, it also involves important challenges for electrical grid operators and conventional power stations at short-medium term that will no longer be able to operate at stable load.

Although the long-term solution will be an efficient combination of appropriate cycling of fossil power plants, a good interconnection of the electric networks and large-scale energy storage systems; the truth is that, for the moment, the first one is the most widespread measure adopted to balance electricity supply and demand.

The unbalance between production and consumption of electrical energy in a power system mainly based on RES is regulated by changing load of fossil fuel power plants (FFPP) which will have to shift their role from providing base-load power to operate in power cycling mode with frequent start-up/shut-down operations and load changing to meet demand variations. This kind of operation does not only deteriorate the equipment but also causes drops in the efficiency of the unit and leads therefore to additional CO_2 emission.

Moreover, load reduction in FFPP comes with a net efficiency reduction. The net efficiency is decreased in 0.8 percentage points each 10% load reduction in coal power plants and up to 1.2 percentage points each 10% load reduction in combined cycles. As a consequence, more fuel (per unit of power output) is needed and specific CO_2 emissions increases, for example up to 20 g/kWh for coal FFPP and 10 g/kWh for combined cycles. The required solutions must maintain the net efficiency as much as possible in the FFPP design values. However, this task becomes impossible when there are frequent load variations in the original installation.

The requirements concerning FFPP flexibility, high load-change velocities and working at the lowest part load possible may significantly be softened by embedding energy storage units. Power-to-Gas technology with its variant known as Power-to-SNG (Synthetic Natural Gas) is one of the best practical options to gain flexibility in FFPP and achieve energy storage [2].

In a PtG system the conversion of surplus electricity, in this case from the FFPP, is carried out by an electrolyser to produce hydrogen. The reaction of this gas with CO_2 through Sabatier chemical reaction (Eq. 1) produces methane and the synthetic natural gas is obtained. The global process involves the inverse water-gas shift (Eq. 2) and CO methanation reaction (Eq. 3) [3]:

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \qquad \Delta H_{298K} = -164.9\ \text{kJ/mol} \qquad (1)$$

$$CO_2 + H_2 \leftrightarrow CO + H_2O \qquad \Delta H_{298K} = +41.5\ \text{kJ/mol} \qquad (2)$$

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O \qquad \Delta H_{298K} = -206.4\ \text{kJ/mol} \qquad (3)$$

Eq. 2 is an endothermic reaction and requires a catalyst, usually nickel or ruthenium-based [4] to be performed at low temperatures, which promote the conversion to methane in Eq. 3.

The proposed system to achieve the new FFPP requirements of fluctuating back-up power includes (i) several electrolysers in parallel able to easily regulate short-noticed demand variations and produce H_2, (ii) a partial CO_2 capture installation of reduced dimensions capable of capture around 10% of CO_2 emissions, (iii) a methanation reactor to produce SNG with H_2 and CO_2 and provide some waste heat for the FFPP and (iv) some storage vessels for CO_2 from Carbon Processing Unit (CPU) and O_2 from electrolyser (see full description in Refs. [5-6]). Oxygen produced could be use in rapid load increases or during very low load operation to maintain steam or local boiler temperatures.

For existing FFPP, the objective of this study is to combine a coal-fired power unit, a small CO_2 capture installation, a Power-to-SNG system and gases storage facilities to achieve extremely flexible and very low CO_2 emission plant. The scheme of such system is shown in Fig. 1.

Load variations are rapidly absorbed mainly (not only) by electrolysers producing H_2 and the boiler and steam cycle of the FFPP can operate uncoupled of the demand evolving with slower and more cost-effective strategies. A CO_2 capture installation of reduced dimensions separates CO_2 from an aliquot of the flue gas to produce, with the H_2, SNG in the methanation reactor. CO_2 storage is needed to increase flexibility and absorb fluctuations.

O_2 generated in the electrolyser is also stored to be injected into the boiler facilitating very low load operation and increasing thermal efficiency. It is not necessary to operate in a fully oxy-combustion mode in existing units but just supply a higher oxygen concentration. The advantages of injection of the oxygen are the reduced stack losses (increasing efficiency with less nitrogen in the flue gases) and lower costs of the CO_2 separation by absorption, as higher CO_2 concentration is reached in the flue gases.

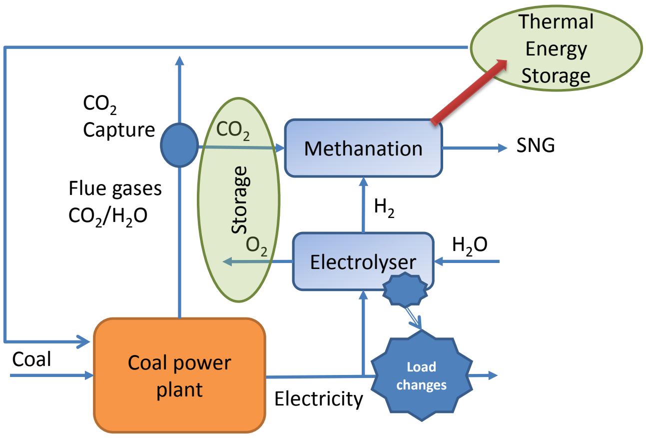

Figure 1. Effect of production of fuels (PTX) on CO_2 emissions

This paper reviews the effects of cycling CO_2 in fossil fuel power plants, proposes a Power-to-SNG concept system for energy storage in the form of methane and quantifies the economic savings when the proposed storage system is integrated in a coal-fired power plant in order to increase the full load hours and to decrease the number of generation outages.

2. Effects of cycling in fossil fuel power plants

The current regulation framework of electricity generation in Europe and in many states of U.S. reduces the full load hours (FLH) and forces to the fossil-fired power plants to work at high variable load with important penalties. As VRE share increases, they must face more frequent unexpected outages and ramp up or down the load looking for rapid and cost-effective strategies to follow the electricity grid requirements. This section reviews the effects of cycling in the main thermal power plants, paying attention to efficiency and emissions.

The effect of the decrease of FLH on energy efficiency is very difficult to be estimated and the results cannot be generalized to other contexts as it involves case-dependent variables as specific generation technology, number and duration of start-ups and shut-downs, level of VRE, or commissioning year.

However, the partial load curves provide the range of decrease in energy efficiency under partial load operation. According to the literature [7], it could mean a decrease of 3-8 percent points (pp) for coal-fired plants and up to 6-17 pp for gas power plants. Typical performance parameters of a subcritical coal power plant (SCPP) and a modern combined-cycle gas turbine (CCGT) are gathered in Tables 1 and 2, respectively, representing the extreme cases with respect to specific emissions, in agreement with current values presented in Ref. [8]. The used low heating values (LHV) for coal and natural gas were 25,8 MJ/kg (w.b.) and 48,2 MJ/kg (w.b.), respectively. Regarding specific emissions, 2,55 kg CO_2/kg-coal and 2,67 kg CO_2/kg-GN were considered. CO_2, NO_x and CO emissions are more than 50% higher for coal technologies, while SO_x is negligible for natural gas.

The decrease in thermal efficiency brings along an increase in specific CO_2 emissions of 9% and 15%, for electricity generation from coal and gas, respectively. NOx emissions decrease with load factor in coal plants, but they are of special interest for gas-fired systems and under minimum compliant load (MCL) can be 3 times higher than under full load [8]. As for CO, emissions for MCL are a half than those of full load for coal plants, while are 15 times higher for gas plants, reflecting a more pronounced decrease in energy efficiency.

Table 1. Performance parameters of a typical subcritical Coal Power Plants at partial load.

Load factor	Thermal efficiency	SFC (kg coal/GJ)	Specific emissions (kg CO_2/MWh)
100	37,5	103,2	948,4
90	38,0	101,9	935,9
80	37,5	103,2	948,4
70	36,9	104,9	963,8
60	36,2	106,9	982,5
50	35,4	109,4	1005
40	34,5	112,2	1031

Table 2. Performance parameters of a typical Combined Cycle Gas Turbine at partial load

Load factor (LF)	Thermal efficiency (η_{Load})	SFC (kg coal/GJ)	Specific emissions (kg CO_2/MWh)
100	53,0	39,15	376,5
90	53,0	39,15	376,5
80	52,5	39,52	380,1
70	51,5	40,29	387,5
60	50,0	41,49	399,1
50	48,0	43,22	415,7
40	46,0	45,10	433,8

Although the significant economic impact of outages, the effect of start-ups and shut-downs is less important on overall energy efficiency, as just a decrease from 0,2 to 0,5 pp is estimated for both technologies [7]. It has to be noticed that these estimates have been obtained under current particular conditions of VRE penetration, but the impacts could be more important when higher shares of variable renewable generation will be achieved.

With regard pollutant emissions, the analysis must be done per event as the specific number of outages depends on many external factors. In Ref. [8] a comparison of specific emission factors for CO, NO_x and SO_x under hot and cold starts can be found for the different technologies. In all cases, emissions during cold starts are from 2 to 16 times higher than those during hot starts, being significantly large the figures of NO_x and CO in gas-fired plants and of SO_x for coal plants. Comparatives about CO_2 emissions during start-ups and shut-downs are not reported.

Additional consequences of cycling regarding the shortened life of equipment derived from a more frequent maintenance and replacement have not been evaluated in terms of efficiency or CO_2 emissions up to date.

All these previous works indicate the great potential of storage systems to develop cost-effective and low-carbon strategies for VRE integration which guarantee the balance between generation and demand. Nevertheless, a rigorous analysis of the effect of Power-to-SNG storage on emissions is not possible from a general point of view due to the high number of hypothesis involved which in turn is case-dependent.

For this reason, the approach tackled in the present paper is from an economic point of view as it is presented in the next section.

3. Cost assessment of shut-down and start-up

The main aim of this paragraph is to estimate the net incomes of an average coal power plant under specific hypothesis and compare the overall costs of stop and start-up with a situation in which a PtG installation is running to avoid the stop due to a reduction in the electricity demand.

As it was previously explained, the regulation of fossil fuel power plant in a scenario where renewable energy produce as much as possible, force the coal (or natural gas) power plant to reduce load. If the required output power is below the minimum load achievable by the power plant, the power plant has to stops and the remaining power is produce by other fossil fuel power plants. In consequence, installations with the lower minimum compliant load could take huge advantage over their competitors to avoid stops in future scenarios with high VRE penetration. In general, this minimum load achievable for coal power plant is around 40% nominal power. If a particular installation is able to reduce this load, for example to 30%, when a load reduction was required, this power plant would remain working, while other would have to stop. So, there are high possibilities that this installation will never arrive to a 30% load as the initially power assigned to the installation that stops must be distributed among the power plants still working.

To illustrate this idea we have supposed a 100 MW_e coal power plant as a reference, with a 5% of ancillaries consumption [9]. The installation is able to sell 95 MW_e to the electric grid. The reference case of this power plant without storage system will be compared to the same station having a Power-to-SNG storage system with capability of 10% of the nominal power, i.e., 10 MW.

It has also supposed that the price of electricity is composed of an availability price of 5€/MWh and a price of pool about 45 €/MWh, that totalise 50€/MWh [10]. Evidently, these quantities vary during the different hours of the day, months and countries but we will consider these fixed values with illustration purposes. Calculations could be also done for other electricity prices in a sensibility analysis at the end of the work. Main hypothesis are summarized in Table 3.

Table 3. Main hypothesis

Variable	Value
Gross Power plant Output (GPO)	100 MW
Power plant Ancillaries	5%
Net Power plant Output (NPO)	95 MW
PtG storage system	10 MW
Pool Electricity Price (PEP)	45 €/MWh
Availability Electricity Price (AEP)	5 €/MWh
Fixed cost (€/day)	22.000 € at full load
Coal fuel cost	11 €/MWh
Natural gas fuel cost	25 €/MWh

Other hypothesis includes the price of fuel (PF): 11 €/MWh for coal and 25 €/MWh for natural gas [11-12]. The power plant will have another “fixed” costs that we have estimated in 22.000 €/day working at full load, 18.700 €/day working at a minimum compliant load (MCL) of 40% and 16.500 €/day when the plant is stopped. The used efficiency values of the subcritical coal power plant as a function of load are those shown in Table 1. Accordingly, fuel costs per day are calculated as:

$$\text{Fuel costs} = 24\ \text{h} \cdot \text{GPO (MW)} \cdot \text{LF} \cdot \eta_{Load} \cdot \text{PF(€/MWh)} \tag{4}$$

Regarding incomes due to sale of electricity and generation availability are given by:

$$\text{Electricity} = \text{NPO (MW)} \cdot \text{LF}_{operation} \cdot \text{PEP(€/MWh)} \quad (5)$$
$$\text{Availability} = \text{NPO (MW)} \cdot \text{LF}_{available} \cdot \text{AEP(€/MWh)} \quad (6)$$

where the load factor (LF) is referred to operation load or to available load, depending on the case.

Under this hypothesis, calculations for 24 hours working at full load show a profit of 21.600 €/day (Table 4). There is an income due to electricity of 114.000 €/day and 70.400 €/day of operational cost (fuel) and 22.000 €/day of fixed cost. Profit reduces with lower loads as illustrates table 4. At 50% of nominal load the profit is very low and at 40% there is a negative profit. In this case the incomes, 46.740 €/day, are lower than the cost due to fuel (30.608 €/day) and "fixed" costs (18.700 €/day). This effect is caused mainly by a reduction of the incomes but also by a reduction of power plant efficiency at lower load. As Table 1 shows, there is a loss of 3 percentage points in efficiency between performance at nominal load and 40% load.

Table 4. Average power plant economic balance per day depending on load

	Full Load	90% load	50% load	40% load	Forced outage
Electricity	102.600 €	92.340 €	51.300 €	41.040 €	0 €
Availability	11.400 €	11.400 €	6.840 €	5.700 €	0 €
TOTAL INCOMES	**114.000 €**	**103.740 €**	**58.140 €**	**46.740 €**	**0 €**
Fuel costs	70.400 €	62.526 €	37.288 €	30.609 €	0 €
Fixed cost	22.000 €	21.450 €	19.250 €	18.700 €	16.500 €
TOTAL COST	**92.400 €**	**83.976 €**	**56.538 €**	**49.309 €**	**16.500 €**
BALANCE	**21.600 €**	**19.764 €**	**1.602 €**	**-2.569 €**	**-16.500 €**

In case of forced power outages, there is a small income due to power plant availability. In principle, a moderate load availability of 40% (later will be reduced depending on the duration of the outage) has been considered as power plant needs some time to start-up and increase load [13]. We have maintained the same unit system (€/day) although it is evident that start-up is a transient process and this quantity does not represent the real costs. In any case it is useful for comparison purposes. Fixed costs are about three quarters of those at full load, related to staff and basic maintenance of facilities. There are not operational costs or electricity incomes, as power plant is stopped.

Moreover, specific costs associated to hot/warm/cold start-up have to be added to these costs related to extra fuel, increment of maintenance and more frequent replacement of equipment because of the shortening of useful life [13]. Table 5 shows the hypothesis used for the calculation of average stop and start costs [14-15]. It can be observed that the cost per day is quite similar in all three cases, but it has to be noticed that for warm or cold starts this quantity must be multiplied by the number of off-grid days. In all cases the economic losses are near to the profit at full load.

Table 5. Average start-up and shut-down costs per day

Type of	Specific costs	Cost per day	Availability	Income	**BALANCE**
Hot (6 hours)	75,0 €/MW	7.500 €	40%	3.420 €	**-20.580 €**
Warm (2 days)	92,0 €/MW	4.600 €	20%	1.710 €	**-19.390 €**
Cold (6 days)	140,0 €/MW	2.333 €	0%	0 €	**-18.833 €**

The most interesting cases for the installation of storage systems are those of low partial load for which the operation is not profitable. Specifically, the economic figures under two hypothetical situations including a PtG storage capacity of 10% nominal load are summarized in Table 6. The first one supposes a demand of 30% nominal power for the particular station, while the second one keeps operative the storage system under an assigned power output of 40% load. Under current operation conditions only in the first situation the power outage occurs. Nevertheless, it is expected the continuous decrease of generation costs as VRE penetration rises and the increase in penalties for CO_2 emissions, not considered in the present work given the very low current price of Ton-CO_2. These forecasts could imply the forced outage of fossil-fired plants at higher load. For this reason, both cases have been analysed under the hypothesis of avoiding stop and start.

The production of the SNG in a Power to Gas facility [5] takes into account the efficiency of both electrolysis and methanation stages. The natural gas incomes considering a global efficiency of 56% to store a 10% of the net power plant at full load are given by:

$$\text{SNG incomes} = 0{,}10 \cdot \text{NPO (MW)} \cdot 0{,}56 \cdot \text{PF}_{GN}(€/\text{MWh}) \qquad (7)$$

The first case include new electricity incomes of 36.480 €/day with respect to the situation of forced outage of Table 4, availability increases in a 10% and fuel and fixed costs are those of 40% load. For the second situation electricity incomes are the same while availability and costs are the corresponding to 50% in Table 4. In both cases the new incomes due to the sale of natural gas, 3.192 €/day, must be included. Without considering savings for avoiding stop and start, the economic balance is negative, even higher, for both cases (-9.637 €/day and -5.466 €/day, respectively). But when the costs shown in Table 5 are accounted for as savings, the figures are very different. Important savings of about 10.000 €/day or higher emerge depending on the start type.

Table 6. Average power plant economic balance avoiding stop and start with 10% load to PtG

	Avoid stop and start. 40% load and net power 30%	*Avoid stop and start. 50% load and net power 40%*
Electricity	30.780 €	41.040 €
Availability	5.700 €	6.840 €
TOTAL INCOMES	**36.480 €**	**47.880 €**
Fuel costs	30.609 €	37.288 €
Fixed cost	18.700 €	19.250 €
TOTAL COST	**49.309 €**	**56.538 €**
NATURAL GAS INCOMES	**3.192**	**3.192**
BALANCE	**-9.637 €**	**-5.466 €**
SAVINGS		
Hot start	**10.973 €/day**	**15.114 €/day**
Warm start	**9.753 €/day**	**13.924 €/day**
Cold start	**9.196 €/day**	**13.397 €/day**

This simple analysis represents the minimum savings of the PtG storage system, as fixed costs have been considered constant, obviating the increase in useful life of equipment and the reduction of maintenance and replacement operations. Additionally, it could operate at higher loads to flatten the load curve, cushioning the frequent load changes by selecting the best option for each situation.

4. Sensitivity analysis

Given the important uncertainties in prices for the next years related to electricity and fuels, this section presents a basic sensitivity analysis considering variations up to the 10% in prices. On the one hand, the results of an increase of availability price up to 5,5 €/MWh and a decrease of pool price up to 40,5 €/MWh are shown in Fig. 2 for the both situations of Table 6. A decrease of about a 25% is observed for all cases, being slightly higher for warm start and larger for 40% load than for 50% load.

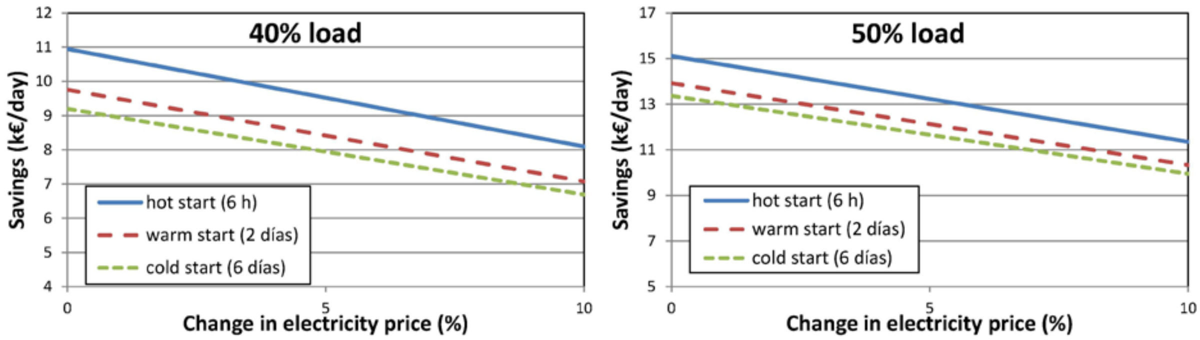

Figure 2. Savings under change in pool and availability prices: a) for a 40% load; b) for a 50% load.

On the other hand, Fig. 3 shows the trends of savings under a 10% increase in gas natural price (up to 27,5 €/MWh) and a 10% decrease in coal price (up to 9,9 €/MWh). Increases in savings range from 26 to 36% depending on the situation. In general, they are lower for 50% load and hot starts, being the cold start at 40% the most favoured case. Nevertheless, at 50% load there is a situation for hot start where the system is able to completely compensate the cost of stop and start the power plant. With fuel price increments of 10% saving are higher than the average start-up and shut-down costs showed in Table 5.

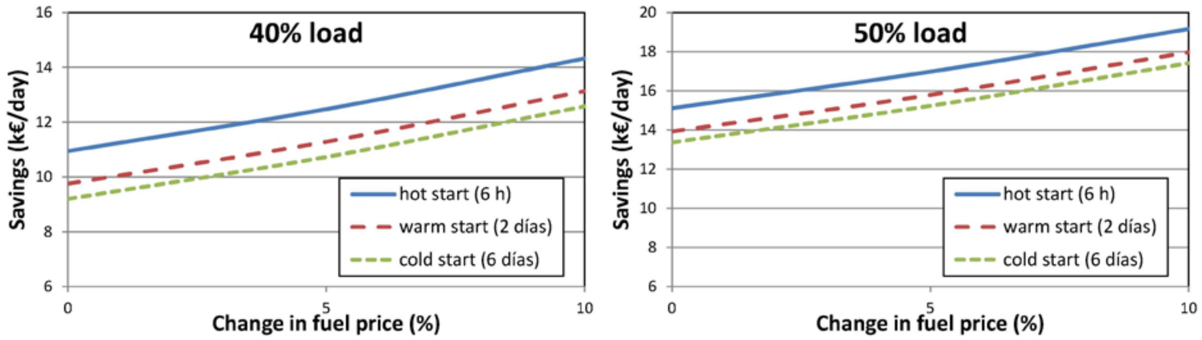

Figure 3. Savings under change in fuel prices: a) for a 40% load; b) for a 50% load.

These situations have been considered the most plausible in an expected framework with higher VRE penetration in the electricity market which predictably will reduce the price of electricity and will demand and reward more flexibility of fossil-fired plants. With respect to fuel prices, if as expected the number of coal plants will be reduced in the future, the price of coal will decrease, while the use of natural gas for the residential and industrial sector will remain or increase, leading to an increase in its price.

5. Conclusions

The increase of the renewable share in the energy generation mix will affect the operational predictability and flexibility of the electricity market. Energy storage systems will be required and this new scenario will also affect the performance of the fossil fuel thermal power plants that have to increase operational flexibility and to face frequent stops and starts that could increase operational cost and reduce their economic results. An option to deal with this problem is to integrate these systems with energy storage options. The present paper has proposed the PtG technology to store excess of electrical energy in form of SNG through the methanation of hydrogen produced by electrolysis. The implantation of PtG could reduce the lower limit of FFPP compliant load before stops, allowing the operation of power plants during periods where the demand is low, avoiding the cost of shut-down and start-up.

The novelty of the paper is to present the integration of FFPP with PtG systems to evaluate and compare the economic costs of FFPP operation with and without energy storage. The results are positive for low load or current situations of forced outages. Without energy storage there are relevant stops and starts costs up to 20.000€/day for a 100 MW FFPP. If a PtG system is installed to avoid stops when load decrease at 40%, the operation usually is still profitless, but there are economic savings of 10.000-15.000 €/day with respect to the previous case, showing that this combination could be economically attractive for utilities.

Moreover, this coupling is able to: smooth the grid power demand fluctuations; avoid start and stops in FFPP; avoid material failure due to thermal stress, ageing and increase of material degradation due to cycling; reduce costs; generate natural gas to be used when demand increase; and avoid fuel external dependency .

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Nomenclature

AEP:	Availability Electricity Price
CCGT:	Combined-Cycle Gas Turbine
CCS:	CO_2 Capture Systems
FFPP:	Fosil Fuel thermal Power Plants
FLH:	Full Load Hours
GPO:	Gross Power plant Output
LF:	Load Factor
LHV:	Lower Heating Value
MCL:	Minimum Compliant Load
NPO:	Net Power plant Output
PEP:	Pool Electricity Price
PF:	Price of Fuel
pp:	Percent Points
PtG:	Power to Gas
RES:	Renewable Resources
SCPP:	Subcritical Coal Power Plant
SFC:	Specific Fuel Consumption
SNG:	Synthetic Natural Gas
VRE:	Variable Renewable Electricity

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