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Report on opportunities and options for PtG in power systems

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Acronyms

AVR	Automatic Voltage Regulator
BM	Balancing Market
CBA	Cost Benefit Analysis
CC	Carbon Capture
CHP	Combined Heat and Power
CCGT	Combined-Cycle Gas Turbine
DAM	Day-Ahead Market
DLNOC	Dry Low NOx Combustors
DSO	Distribution System Operator
EBITDA	Earnings Before Interest, Taxes, Depreciation and Amortization
ES	Electricity System
FTR	Financial Transmission Rights
HV	High Voltage
HW	Hardware
IEC	International Electro technical Commission
ISO	Independent System Operator
Li-Ion	Lithium Batteries
LV	Low Voltage
MV	Medium Voltage
NaS	Sodium Sulphur Batteries
NG	Natural Gas
NPV	Net Present Value
OCGT	Open-Cycle Gas Turbine
OEM	Original Equipment Manufacturer
OSL	Operational Security Limits
PtG	Power-to-Gas
PHES	Pumped Hydroelectric Energy Storage
PV	Photovoltaic
RES	Renewable Energy Sources
SW	Software
SNG	Synthetic Natural Gas
TSO	Transmission System Operator
VPP	Virtual Power Plant
VRBF	Vanadium Redox Flow Batteries

Executive Summary

The introduction of large shares of energy from renewable resources (RES) led to a different paradigm in the management and operation of the electricity system (ES). In fact, once the electricity is produced, it has to be used ("just-in-time" use): the shift of the generated electricity over the time horizon is possible only by implementing proper storage technologies.

This report aims to investigate the role of Power-to-Gas (PtG) in the electrical system, in particular drawing its possible use in the different sectors of the ES. Since one of the partners involved has special expertise in the operation of gas-fired power plants, coupling PtG with such plants was chosen as first application for a deeper investigation. The study includes the technical and legislative aspects involved in the use of Synthetic Natural Gas (SNG) as fuel for gas turbines.

For clearly defining PtG applications and their interactions with the ES, a general scheme of the different dimensions of the ES has to be defined, which is composed of five different categories:

D1) *Systems* represent the different sectors composing the ES, i.e., generation, transmission, distribution and utilisation;

D2) *States of the system*, which are indicative of the system condition in the considered time instant, i.e., normal, alert, emergency, extremis, and restoration;

D3) *Operation of the system*, which indicates the activities performed for maintaining the system in operation. i.e., feasibility assurance in normal condition, efficiency improvement, reliability improvement, and service restoration;

D4) *Time frame*, which is indicative of the analysis for different aspects of the ES operation.

D5) *Market* environment, which indicates the different platforms, where the trade of energy and interrelated services are performed, i.e., energy market and ancillary services market.

Following the aforementioned dimensions, a thorough literature review has been performed on SNG-related applications under the effect of ES. The review has clearly shown that most of the existing literature refers to the application of PtG for the management of the transmission system in case of excess of RES, while some studies are also available regarding the coupling of PtG with generation plants and the applications of PtG in distribution systems. However, there is a lack of studies dealing with the application of PtG (interpreted as power-to-methane) in the utilisation sector. The time frame typically used in the existing studies refers to 1 day to a year, and, in line with this fact, the day-ahead market is the commonly used framework. Moreover, all studies consider the normal state of the system and are devoted to assure the feasibility of the system in normal conditions.

This report focuses on the generation side (part of the dimension D1) and three different applications have been investigated. More particularly, the first two applications refer to the coupling of PtG plants with gas-fired power plants, aiming to cover the power plant unbalances and to offer the downward capacity in the ancillary services market. The last application refers to the use of PtG coupled with a RES plant, to allow the participation of the RES-based power plant to the ancillary services market, by introducing the dispatchability also for RES-based power plants. The dispatchability is guaranteed by installing clusters of micro-turbines.

The results show that, due to the structure of the remuneration scheme, the use of PtG for covering the plant unbalances does not fit well with the characteristic of the PtG plant, even if the use of PtG allows to recover large part of the excess of generation.

The application regarding the possible use of the PtG for offering downward capacity in the ancillary service market shows that, also in this case, the remuneration mechanism does not favour PtG. In fact, the costs in terms of additional fuel burnt by the gas-fired power plant for supplying the electrolyser are not recovered by selling the produced SNG, and the best option is to act on the operation of the gas-fired power plant. It is worth to note that also the use of batteries for offering downward capacity on the market is not convenient, and the use of batteries becomes fruitful only by offering upward capacity on the market as well.

In case of coupling PtG facilities with RES-based power plants, the excess of generation (which should be cut, e.g., due to network constraints) has to be carefully considered. In fact, in case of high excess of generation, the most convenient investment would be the coupling of small PtG facilities with small clusters (production of methane limited and production of electricity made by using small electrical components), or big PtG facilities (that means large SNG production) coupled with electrical facilities, which can properly exploit it (relatively large size).

For getting a clearer picture of the use of PtG with RES-based power plant, the report starts from the analysis of different existing European markets, (i.e, North Pool, Italy, Austria/Germany, France and Switzerland), for providing an evaluation of the incentive necessary for making PtG feasible. The use of PtG with a RES-based power plant for producing SNG to sell in the market is interesting, even if incentives are necessary for a reasonable payback time (in all the countries analysed it has to be at least 60 €/MWh).

The possible utilisation of SNG for feeding gas turbines has to face the environmental rules introduced in the last years. Taking Italy as example, and referring to European directives approved as law in the Italian legislation, it has to be noted that legislation regarding the process of production of SNG takes into account the risk of having stored gas in the area of the plant. For a PtG plant (also associated to a gas-fired power plants), it is necessary i) to understand which gases are stored, ii) to evaluate their hazard potential (e.g., if they are flammable or toxic) and iii) to estimate the quantity eventually stored. Natural gas is the desired fuel for gas turbines, but this fuel must be clean dry gas, especially for an advanced-technology gas turbine. This condition is necessary because the Dry Low NO_x Combustors (DLNOCs) are very sensitive to any liquid carry-over into the combustor, which leads to failures due to flashback problems in these combustors.

To sum up, this Deliverable gives an overview of possible applications of PtG in electricity systems. Specific applications involving gas-fired power plants have been analysed in detail. An outlook on further applications promising for investigation is provided.

1 Introduction

This reports aims to:

- Introduce a framework highlighting the features of the ES, which have to be compared with the characteristics of the technology PtG (Sections 2–2.5);
- Investigate the literature, involving the application of PtG into the ES (Section 3);
- Classify the papers found in literature by using the suggested dimensions (Section 4);
- Present the analysed applications involving both PtG and dispatchable power plants, by including t the model of the electrolyser, obtained by using real data (Section 5);
- Present the analysed applications involving both PtG and non-dispatchable power plants (Section 6);
- Present the legislative and technical constraints in the use of SNG as fuel for gas turbines (Section 7).

All the above sections will allow to have a clearer idea of the status of the applications of PtG into the ES, as well as to provide a perspective of the future developments. The study of some applications based on real data suggests some remarkable features (classified by following the introduced framework), which have to be considered for guaranteeing a proper evaluation of the PtG technology.

In recent years, a large number of generation plants based on the exploitation of renewable energy sources (RES), has been installed all over the world. This fact, considered with the urgent need to reduce carbon emissions [1], led researchers to focus on implementation of possible methodologies allowing the complete exploitation of the RES production for supplying the energy system. In the literature, some studies prospect the creation of 100% RES supplied energy systems [2], whereas some other focus their attention on the possibility to manage a 100% RES-based electricity system (ES) [3].

One of the reasons of the increasing interest about this topic is the nuclear accident of Fukushima, that led in Germany to the so-called consequent “Energiewende” [4]. This term indicates the transition of Germany from an energy system based on exploitation of nuclear and fossil fuels, to a low-carbon energy system: in that way, dismissing nuclear power plants will be possible without any energy ‘shock’. Furthermore, most of the wind farms are located in the north of Germany, whereas the south of the country presents a massive load. This fact led to highlight the necessity to find a mean for somehow moving large amounts of energy from north to south. By considering the social un-acceptance of new overhead lines, together with the existence of a widespread gas infrastructure, the idea has come up to use the gas infrastructure as storage facility, and then the energy transportation could be made by gas instead of by electricity.

Considering this background, the introduction of more flexibility in the ES is a challenge, such that the RES curtailment can be reduced as much as possible [5][6][7]. Beyond the capacity to add more flexibility to the system, PtG is able to couple the ES with other energy systems, such as district heating [8] and transport [9]. Furthermore, the long-term storage is another important issue to be solved in a 100% RES-based energy system, and PtG can represent a promising solution [10]. The introduction of the concept aiming to produce synthetic natural gas (SNG) and to store energy by means of it can be traced back to Long in 1978 [11]: the patent described the conversion of electricity into gas, the consequent feeding of public gas networks and the production of electricity for solving electrical load peaks. A number of demonstrations sites have been installed in the last year around the world, which indicates a great interest in this technology [12].

So far, the connection between gas and electricity infrastructures was guaranteed by means of Gas-to-Power facilities, i.e., Combined-Cycle Gas Turbine (CCGT) power plants and Open-Cycle Gas Turbine (OCGT) power plants, and now the other conversion direction can be provided by PtG. An example of the potential paths and connections is shown in Figure 1-1. In the figure, blue lines represent the gas vector, red lines represent electricity, green lines refer to heat, whereas H_2 is indicated by grey lines.

Gas can supply the customer as it is (for heating and mobility), or be converted either into heat or mechanical energy or electricity. The electricity vector is usually provided to the customer as it is, but a possible conversion into gas (SNG or H_2) or heat is also possible. The heat vector is served by starting both from electricity and gas, and its distribution can be done by district heating systems. Finally, possible applications of H_2 are in the mobility sector, SNG production, or conversion in mechanical energy and heat. Indeed, PtG is a significant entry with growing integration within the multi-energy generation framework [13].

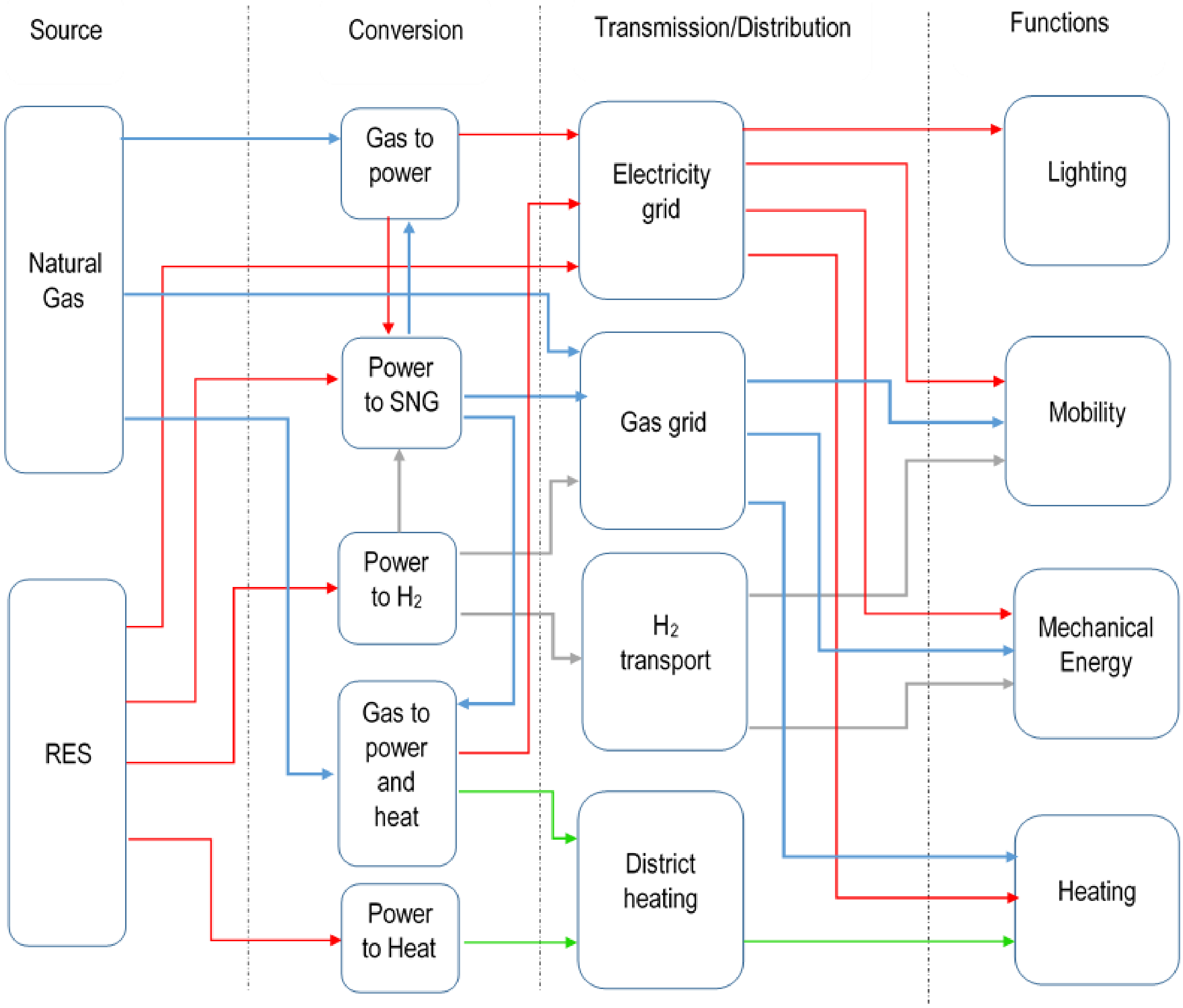


Figure 1-1: Dimensions of studying electricity power systems for PtG [14]
gas, electricity, heat, H_2

Generally speaking, the term PtG states different processes and thus different final products (i.e., hydrogen [15][16] and SNG [17][18]). However, the focus of this report is concentrated on the production of SNG (also named methanation), even though some applications only involving H_2 are presented, for highlighting their possible upgrade with a methanation step.

It is worth to note as introductory remark that the evolution of the ES in the future is still uncertain, due to the presence of two different schools of thought. The first one believes that in the future the ES will be essentially based on “supergrids” [19], whereas the second one thinks that the future ES will be essentially composed of many “microgrids” [20]. The term supergrid indicates an infrastructure based on High Voltage (HV) systems allowing the transfer of large amounts of energy on long distances with low losses. In this case, the generation point and the load point are located far apart from each other, and the electrical infrastructure allows the connection between them efficiently (i.e. with low losses). In case of microgrids, the electrical infrastructure is based on Medium Voltage (MV) or Low Voltage (LV) systems. This infrastructure connects the load and the generation points, which are close to each other. The aim in this case is to create “small” electrical systems that can operate in “island” mode, i.e. not connected to the main network. These two visions are both compatible with the use of PtG, due to the scalability of the technology, even if the scale of the PtG technology used is different (from few kW within microgrids to MW within supergrids).

2 An overarching framework for characterising electricity systems

For clearly defining PtG applications and their interactions with the ES, a general scheme of the *different dimensions* of the ES has to be defined, so that a precise classification can be performed (Figure 2-1).

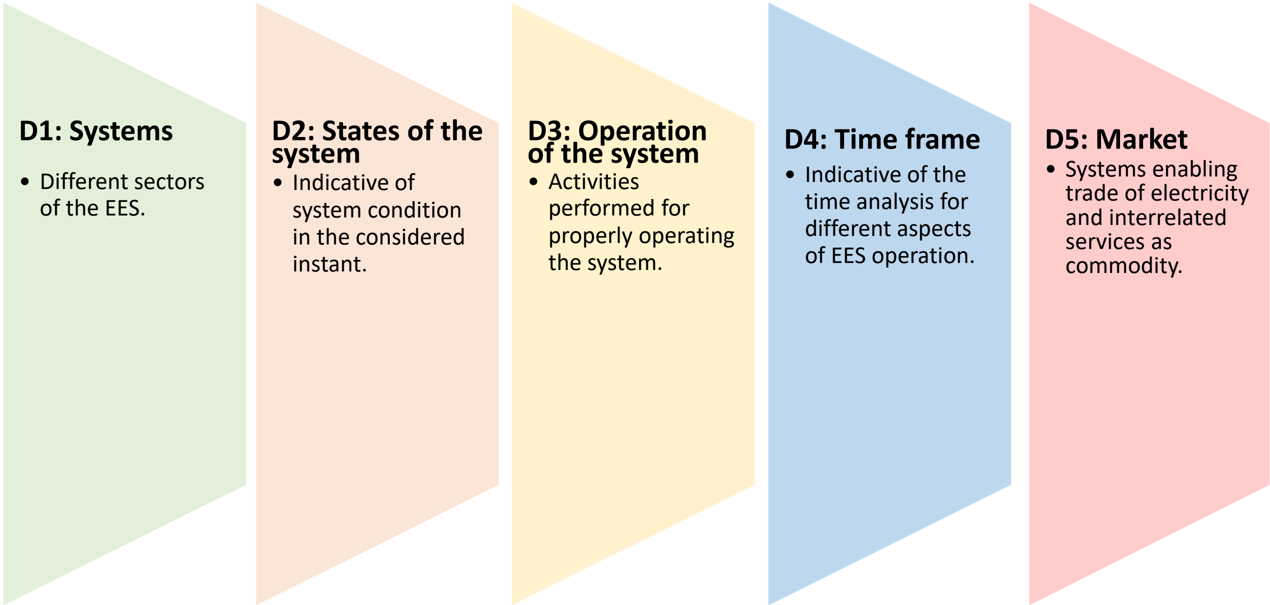


Figure 2-1: Dimensions of studying electricity power systems

For the sake of clarity, a brief description of the dimensions and subdimensions is given here, while providing more details in the respective sections of this document.

With reference to Figure 2-1, the following dimensions and subdimensions have been defined:

D1) *Systems* represent the different sectors composing the ES, i.e.:

a. Generation: represents all the activities aiming to convert primary energy (chemical, mechanical, and so on) in electricity.

b. Transmission: represents the infrastructure aiming to transfer electricity from the production points toward the load centres.

c. Distribution: represents a secondary level infrastructure that allows bringing electricity from the ending point of the transmission network to the customers.

d. Utilisation: represents all the customers supplied by the ES.

D2) *States of the system* are indicative of the system condition in the considered time instant, and can be classified in:

a. Normal: it is the typical operation condition of the system, when all the variables lie in the feasible ranges.

b. Alert: the system still operated properly, but it is identified a condition that can bring the system to the emergency state.

c. Emergency: the system is characterized by some operative variables out of the normal ranges.

d. Extremis: condition in which the system is no longer working (e.g., blackout).

e. Restoration: condition post-extremis, when the system is managed for bringing it again back to the normal state.

D3) *Operation of the system is* indicative of the activities performed for maintaining the system in operation. They can be divided in:

a. Feasibility assurance in normal condition: it represents all the activities that allow meeting all the system constraints.

b. Efficiency improvement: it aims to operate the system in the most efficient way.

c. Reliability improvement: it represents all the activities carried out for ensuring a reliable system (e.g., maintenance plan).

d. Service restoration: it represents all the activities performed for restoring the service in case of fault (e.g., reconfiguration plan).

D4) *Time frame* is indicative of the analysis for different aspects of the ES operation.

D5) *Market* indicates the different platforms where the trade of energy and interrelated services are performed. They are:

a. Energy market: where operators sell and buy electricity.

b. Ancillary services market: where the system operator buys energy and capacity for guaranteeing the safe operation of the system.

The synoptic view of the different dimensions and sub-dimensions is shown in Table 2-1.

By following the coding reported, it is possible to define any application with the characterization introduced. Some examples of applications characterized by using the dimensions indicated above are reported in Section 4.

Table 2-1: Synoptic representation of dimensions and sub-dimensions for PtG applications

Dimension		Subdimension	
D1	System Structure	D1.1	Generation
		D1.2	Transmission
		D1.3	Distribution
		D1.4	Utilisation
D2	State of the system	D2.1	Normal
		D2.2	Alert
		D2.3	Emergency
		D2.4	Extremis
		D2.5	Restoration
D3	Operation of the system	D3.1	Feasibility assurance in normal operating conditions
		D3.2	Efficiency improvement
		D3.3	Reliability improvement
		D3.4	Service Restoration
D4	Time frame	D4.1	≈ 1 μs–100 ms
		D4.2	≈ 1–10 s
		D4.3	≈ 1–10 min
		D4.4	≈ 15 min – hours
		D4.5	≈ 1day to year
		D4.6	≈ 5–10 years
D5	Market	D5.1	Energy
		D5.2	Ancillary services

2.1 Dimension 1: Structure of the system

The first dimension analysed is the *structure* of the system. As shown in Figure 2-2, the ES structure is composed of four sub-dimensions, which are described below.

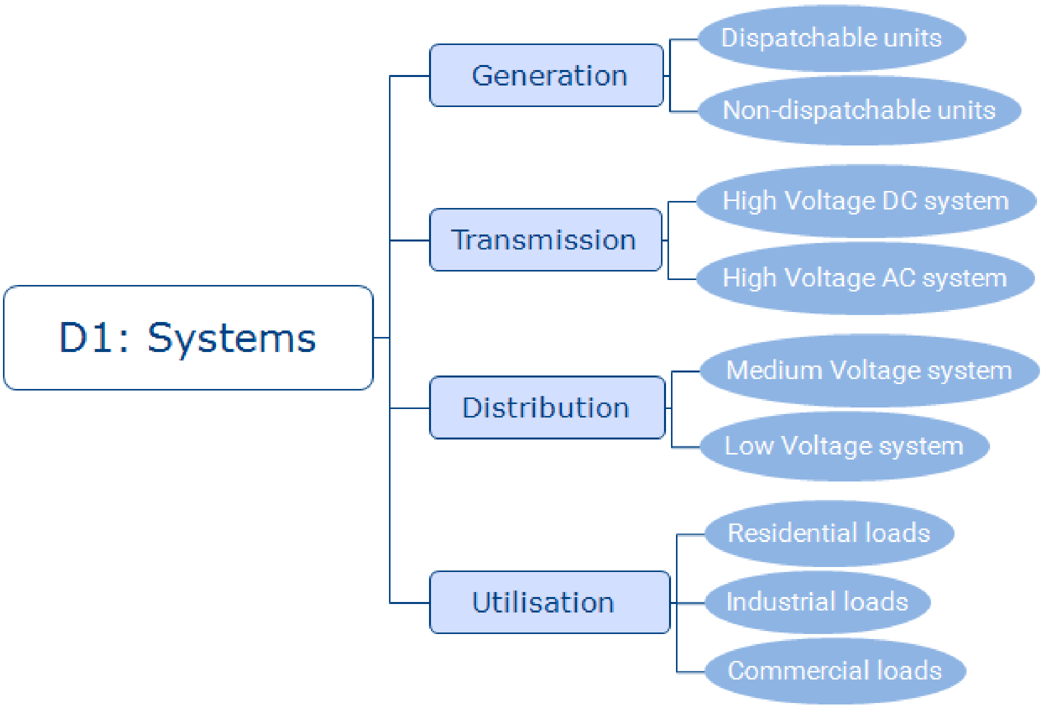


Figure 2-2: *System* dimension with sub-dimensions and sub-dimension specifications

2.1.1 Generation

The term *generation* indicates the production of energy [21].

Depending on the possibility to control their output, the units can be divided in:

- *Dispatchable* units: units that can be controlled by reducing the amount of fluid flowing in the turbine (and eventually this allows to control the output power), and for this reason they participate in the dispatching process.
- *Non-dispatchable* units: new types of generators using natural primary sources (generally indicated as renewable sources), which cannot be properly controlled, thus they cannot participate in the dispatching process. Their production can be cut only when it would cause trouble to the operation of the electrical system.

The representation of the production over time is made by using the *generation pattern*, usually obtained from measurements performed at the interface between the generation unit and the network. The generation pattern shows, for each time interval, the mean value of power in the time step considered: the energy provided to the network at each time step is calculated by multiplying the value of the average power at each time step and the time step duration.

In Figure 2-3 and in Figure 2-4 two examples of real generation patterns are reported, showing respectively a photovoltaic (PV) plant production and a Combined Heat and Power (CHP) plant, both of them expressed in per unit (pu) with respect to their nominal power.

For the PV plant the data are provided minute-by-minute, whereas the generation pattern of the CHP is available in 15-min time steps (but a general rule about the time resolution does not exist and it is related to the measurement system characteristics and to the purpose of the study based on the measurement).

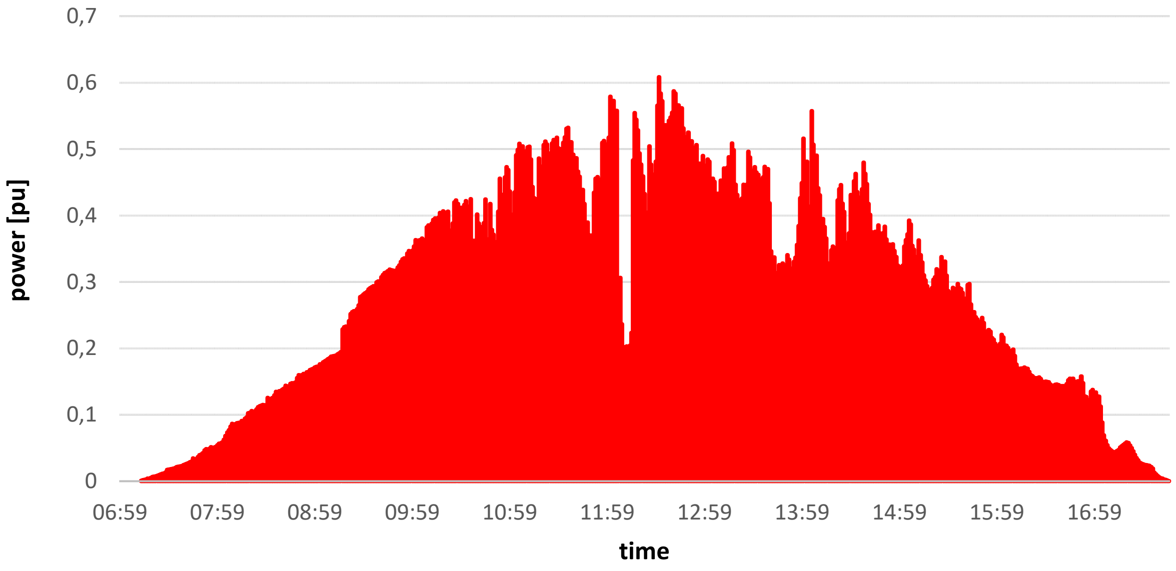


Figure 2-3: Generation pattern of a PV plant; normalised power vs. time

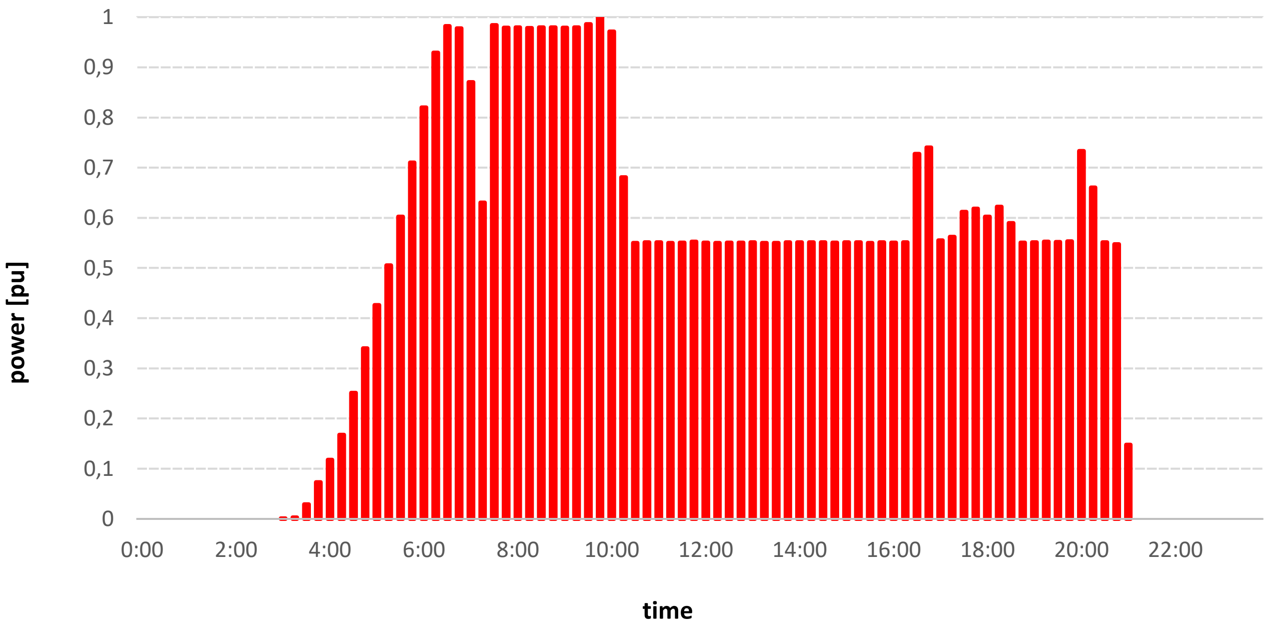


Figure 2-4: Generation pattern: CHP plant; normalised power vs. time

For the study of PtG applications in the presence of renewable energy, the variation of the power in time could be interesting for highlighting the dynamic characteristics of the PtG-electrolyser for properly exploiting the renewable production.

Without loss of generality, the same PV pattern shown in Figure 2-3 is considered here: in particular, in Figure 2-5 on the vertical axis, the variation expressed in percentage with respect to the nominal power of the plant is shown. In a minute (that is, the time step duration for the considered generation pattern), the maximum increase is about 25%, while the maximum decrease is about 33%. This large variation can be smoothed in case of several renewable power plants connected at the same network portion, and fed by different sources (e.g., wind and solar). In fact, because of the diversity of the sources during time and along space, this problem is strongly reduced.

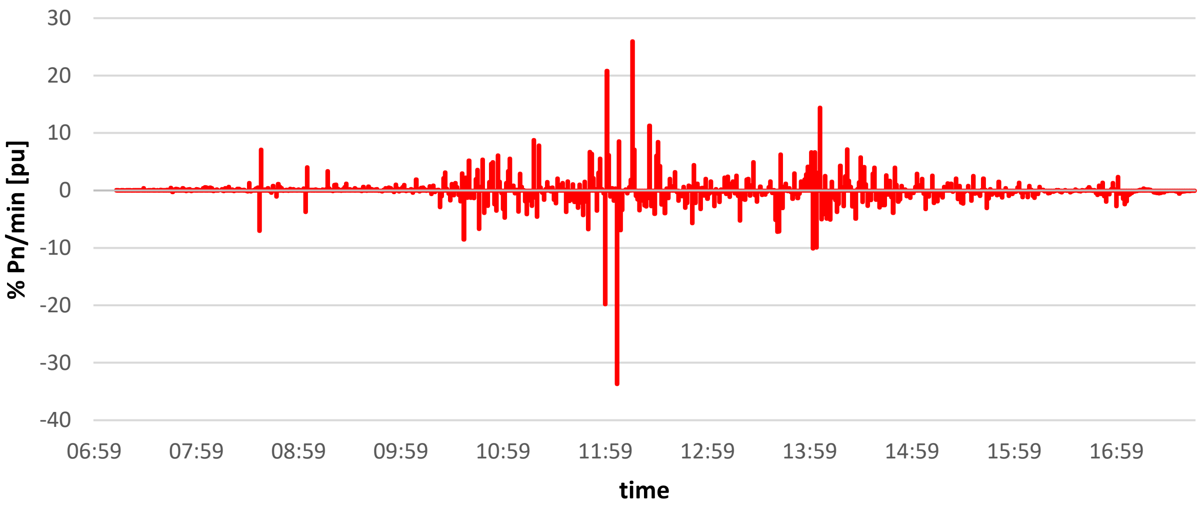


Figure 2-5: Percentage variation of the generation in 1-min steps for PV plant

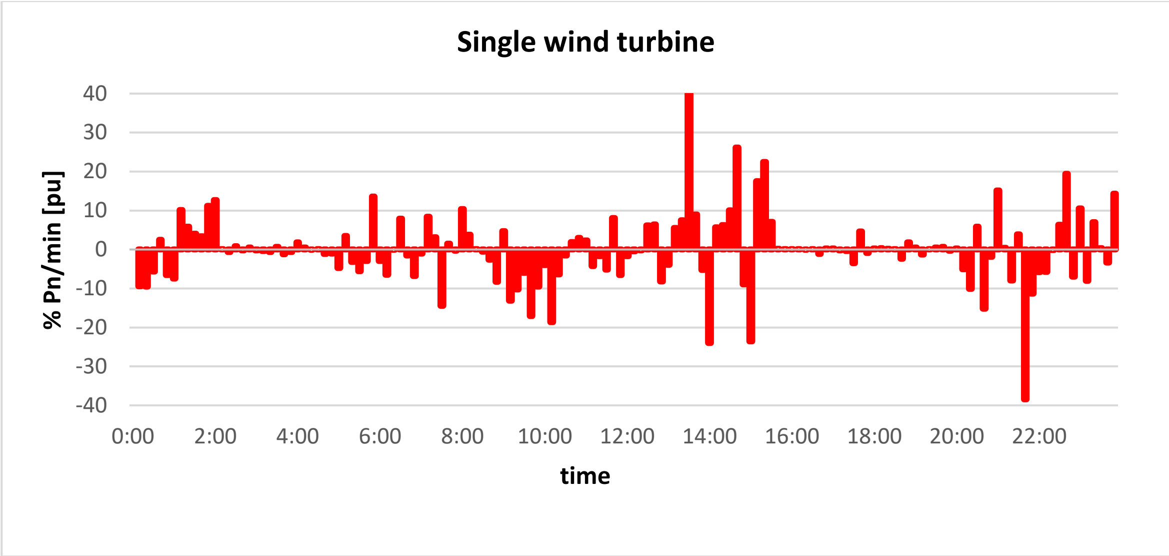
For showing this, the measurements carried out on a wind park composed of 31 wind turbines are considered.

In Figure 2-6, the percentage variation of the generation in the time step considered (i.e., 10 minutes) is shown (both expressed in pu, by considering as reference power the nominal power of a single turbine, and the nominal power of the wind park, respectively). As it is possible to see, the maximum increase and decrease in the time step is much lower for the wind park (Figure 2-6b) than for a single turbine (Figure 2-6a).

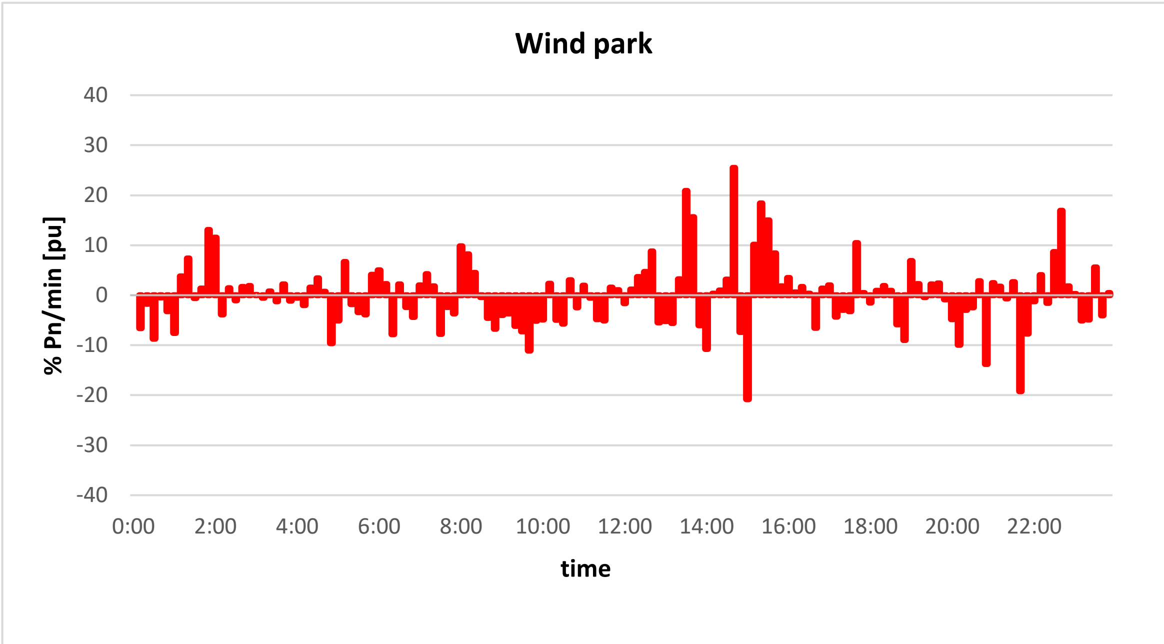
The maximum values are summarised in Table 2-2.

Table 2-2: Effect of the diversity on generation variation

	Maximum increase (in 10 minutes)	**Maximum decrease (in 10 minutes)**
Single turbine	42%	–38%
Wind park	25%	–20%



(a)



(b)

Figure 2-6: Percentage variation of the generation in 10-min steps for single wind turbine (a) and wind park (b)

2.1.2 Transmission

The transmission system is composed of all the lines (overhead and cables) operated at the High Voltage (HV) level. As specified in the IEC dictionary [22] "The boundaries between medium- and high-voltage levels overlap and depend on local circumstances and history or common usage. Nevertheless the band 30 kV to 100 kV frequently contains the accepted boundary".

In any case, from the topological point of view, the transmission system has a meshed structure, and it is operated as a meshed system.

2.1.3 Distribution

The distribution system represents all the networks not described by the definition of the transmission network, i.e., all the networks operated in MV and LV. Typically, each portion of the distribution system starts from a substation fed by transmission lines, and represents the interface between loads and the transmission system. The voltage levels are different from country to country, and often even in the same country different values do exist [23].

The distribution system has a weakly-meshed structure, but it is typically operated as a radial system (i.e., it is not possible to recognize a closed loop): the presence of redundant branches allows a faster reconnection of the loads in case of network fault [24]. Because of the radial operation, faults occurring in the distribution system cause the vast majority of the customer interruptions. For residential loads, about 80% of the time without supply can be attributed to faults on the distribution system [24][25].

By definition, a *feeder* represents the portion of a network starting from a substation and supplying several loads, even geographically dispersed in a wide area [23]; in other words, each radial path which can be found in the system is called feeder. More than one feeder can be supplied by a single HV/MV substation.

Each feeder is usually composed of more than one line, connecting either different MV/LV kiosks (in case of an MV network) or different LV supply points (in case of an LV network, usually three-phase).

The distribution system is composed of both overhead lines and underground cables. It has been calculated that about 35% of the entire system is composed of underground cables, whereas the remaining part is composed of overhead lines [25].

2.1.4 Utilisation

The utilisation side is composed of *all the users* withdrawing power from the electricity system, at different voltage levels.

A common classification divides the users into residential, industrial and commercial consumers [24]. Other classifications point out the different level of voltage supplying the loads (in any case, typically only industrial loads are supplied at HV level).

Similarly to the representation used for generation, for the loads the proper representation can be obtained by means of load curves [23][24], defined as the expected demand of a customer over time.

Also for them, the diversity among different loads brings to aggregate load curves that are smoother than the curves of each single customer.

Some useful definitions for defining load curves are [23]:

- Demand: it is represented by the average power over the time step considered, and by multiplying the average power by the time interval duration the energy for the specific time step is calculated.

- Average demand: it is the average of the demands over a defined time interval. It is important to note that the *demand* refers to a *single time step*, while the *average demand* refers to a *time interval*. Both are calculated as the ratio of the energy in the time period considered (time step or time interval) to the duration of the time period.

- Maximum demand: it is the peak load during a defined time interval (e.g., a day).

- Maximum non-coincident demand: it is the sum of the peaks of all the loads (in a defined time interval). It is important to note that the peaks can happen in different time steps.

- Diversified demand: it is the sum of a group of loads, for example supplied by the same feeder. Because of the diversity of the loads, the maximum diversified demand is lower than the maximum non-coincident demand (because usually the peaks for different loads happen at different time instants).

- Maximum diversified demand: it is the peak of the diversified demand over a defined time interval.

- Load factor: it is the ratio of the average demand to the maximum demand, both determined over the same time period.

2.2 Dimension 2: States of the system

The state of the system indicates its condition in the considered instant. Without loss of generality, the following system states can be listed:

1) *Normal* state: all the control variables (system frequency, voltage, and transmission power flow) lie within their limits, and the reserve requirements[1] are being met; thus, both equality and inequality constraints[2] are verified (see Figure 2-7).

2) *Alert* state: the control variables still are in the operating ranges, but the reserve requirements are not fulfilled; therefore, in case of occurrence of one fault, the normal state could not be maintained anymore.

3) *Emergency* state: the system is outside from the normal operating ranges; the inequality constraints are not verified (for example, a line is overloaded).

4) *Extremis* state: the system is no longer working, and thus both inequality and equality constraints are not verified (because the balance between input and output)

5) *Restoration* state: the system is operated for allowing the restarting after a black out.

[1] Reserve margins: amount of power which has to be available for guaranteeing the fulfilment of the frequency standard

[2] Equality constraint: instantaneous equality between generation and load;
Inequality constraints: representing the upper and lower limits to the voltage value, and line flow limits

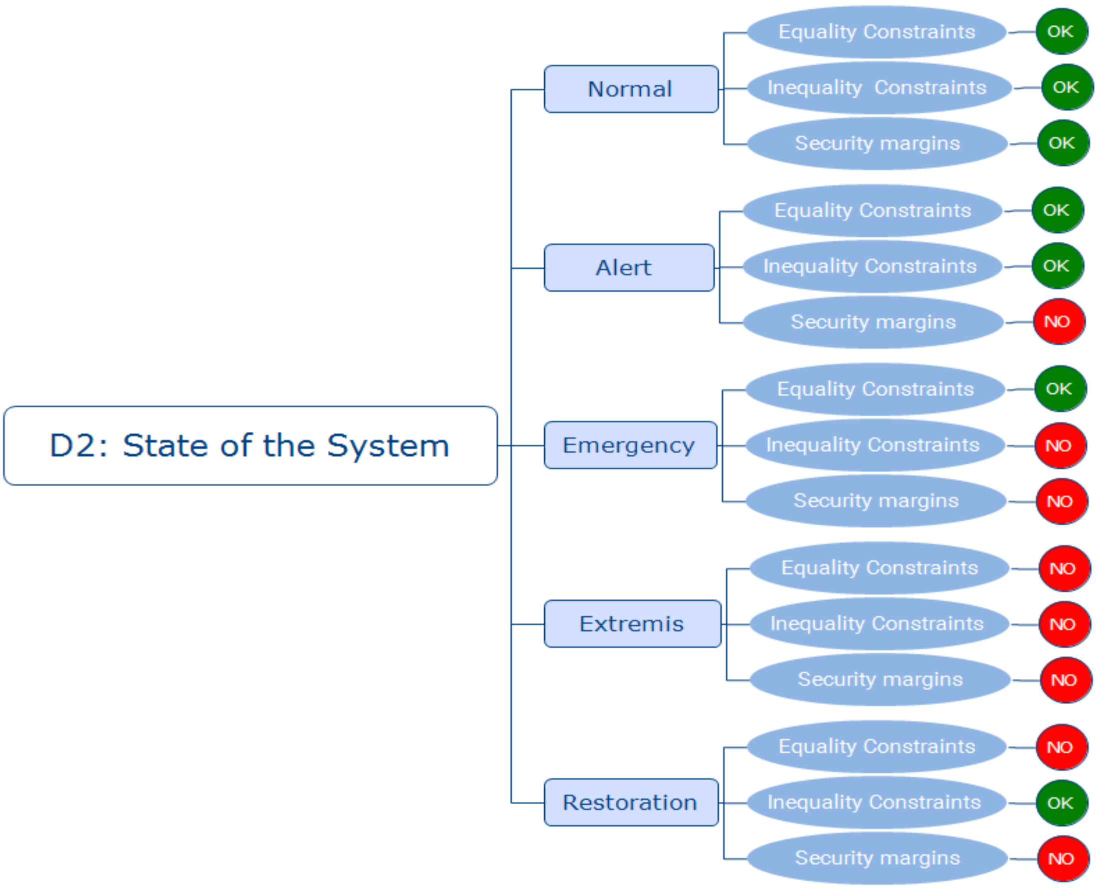


Figure 2-7: Mind map of the State of the System

For the sake of clarity, the different sectors composing the ES are analysed, for highlighting some peculiar characteristics of them.

2.2.1 Generation units

Because of the different nature of dispatchable units, different safety protocols and procedures are usually applied.

One important aspect that needs relatively long time for being performed is the *maintenance*, which has to be planned in advanced to reduce as much as possible the non-operating time of the unit.

In any case, the general structure follows the five states listed above.

2.2.2 Transmission system

The states of the transmission systems have been well investigated in the past [26], and for this reason it is possible to find common definitions recognized at international level (e.g., ENTSO-E).

In Figure 2-8, a block diagram showing all the transmission system states and the connections among them is presented [27]. In the diagram, the letter *E* indicates the equality constraints (i.e., the instantaneous equality between generation and load), while the letter *I* indicates the inequality constraints (i.e., voltage value and line current limits).

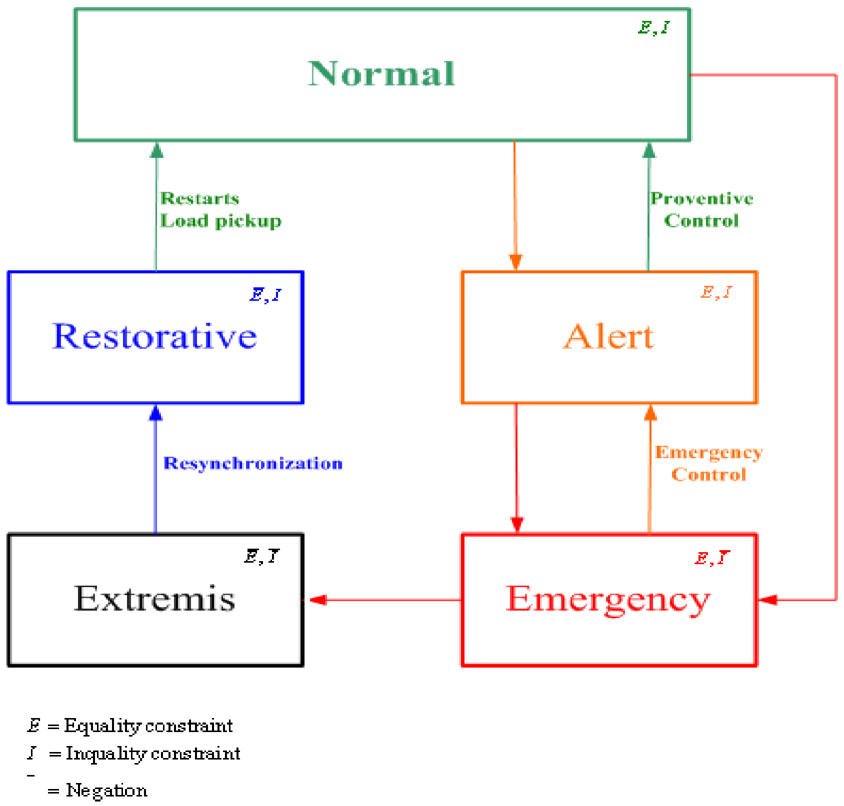


Figure 2-8: Diagram flow of the State of the System [27]

The state of the transmission system [28] characterises the system operation in relation to the Operational Security Limits (OSL), reported in Table 2-3, Table 2-4 (both[3] for voltage requirements) and in Table 2-5 (for frequency requirements).
The OSL could not be respected in case of fault (i.e., *contingency*) of one or more components of the system [28].

The set of possible contingencies that must be simulated for guaranteeing the safety of the system is indicated in the contingency list[4], and is simulated during the contingency analysis.

Table 2-3: Voltage ranges for reference voltages defined by TSOs between 110 kV to 300 kV [28]

Synchronous Area	Voltage range [pu]	Time duration
Continental Europe	0.90 – 1.118	unlimited
Nordic	0.90 – 1.05	unlimited
Great Britain	0.90 – 1.10	unlimited
Ireland	0.90 – 1.118	unlimited
Ireland offshore	0.90 – 1.10	unlimited
Baltic	0.90 – 1.12	unlimited

[3] The values are expressed in per unit (pu), by considering as reference the rated voltage of the system.
[4] The contingency list has to be prepared by the TSO for its own system. Examples of contingencies are 'out of service of one line', 'fault of transformers', 'loss of a large generator', and so on.

Table 2-4: Voltage ranges for reference voltages defined by TSOs between 300 kV to 400 kV [28]

Synchronous Area	Voltage range [pu]	Time duration
Continental Europe	0.90 – 1.05	unlimited
Nordic	0.90 – 1.05	unlimited
Great Britain	0.90 – 1.05	unlimited
Ireland	0.90 – 1.05	unlimited
Ireland offshore	0.90 – 1.10	unlimited
Baltic	0.90 – 1.10	unlimited

Table 2-5: Frequency Quality Defining Parameters of the Synchronous Areas [29]

Synchronous Area	Continental Europe	Great Britain	Ireland	Nordic
Standard Frequency Range [mHz]	±50	±200	±200	±100
Maximum Instantaneous Frequency Deviation [mHz]	800	800	1000	1000
Maximum Steady-state Frequency Deviation [mHz]	200	500	500	500
Time to Restore Frequency [min]	15	10	20	15
Alert State Trigger Time [min]	5	10	10	5

The different states of the ES are:

1) Normal

Normal State means that the system operated within its OSL both in the N-Situation and after the occurrence of any contingency from the contingency list, taking into account the effect of the available remedial actions.

The N-situation occurs when no element of the transmission system is affected by fault.

In the normal state, the following characteristics have to be verified:

a. voltage and frequency deviation are within the OSL defined above;

b. active and reactive power reserves are sufficient to withstand contingencies from the contingency list.

Therefore, the power system is able to deal with contingencies.

2) Alert

Alert State means that the system operates within its OSL, but there is at least one contingency coming for which, in case of occurrence, the available remedial actions are not sufficient to keep the normal state.

The following points characterize the alert state:

a. voltage is within its OSL defined above;

and

b. at least one of the following conditions is fulfilled:

- active Power Reserve requirements are not fulfilled with lack of more than 20% of the required amount for more than 30 minutes and with no means to replace them;
- frequency is within the frequency limits for the Alert State as defined in [29];
- at least one contingency from the contingency list can lead to deviations from Operational Security Limits, even after effects of Remedial Actions.

3) Emergency

Emergency State means that the system violates the OSL and at least one of the operational parameters is outside of the respective limits.

In more detail, this means that at least one of the following situations is happening:

a. there is at least one deviation from Operational Security Limits and times;

b. frequency is outside the frequency limits for the Normal State and outside the frequency limits for the Alert State as defined in [29];

c. at least one measure of the System Defence Plan is activated;

d. all the tools and facilities for monitoring the System State of the Transmission System, means for controlling switching, means of communication with control centres of other TSOs and tools for Operational Security Analysis are out of operation for more than 30 minutes.

4) Blackout

The blackout state corresponds to the state Extremis shown in Figure 2-8.

Blackout State means that a part or the whole transmission system is no longer in operation.

The blackout condition is verified after:

a. the loss of more than 50% of load in the TSO Responsibility Area

or

b. the total absence of voltage for at least 3 minutes

is registered.

5) Restoration

All the procedures implemented to bring frequency, voltages and other parameter within the operational security limits are part of the restoration process.

2.2.3 Distribution system

The number of distribution companies in Europe is about 2,400; most of them operate in a single country. The number of customers supplied is 260 millions and most of them (about 99%) are residential or small business customers [30].

1) Normal operation

Each distribution operator has to guarantee a reliable supply to the customer and allowing a non-discriminatory access to the network for all retailers [30].

2) Alert

When the inequality constraints are not respected (e.g., voltage out of the allowed ranges and overloaded lines), the DSO can either shed some loads or cut the excess of RES production [31].

3) Emergency and restoration

In case of fault (e.g., a tree hitting a countryside overhead line), a reconfiguration procedure is applied, for restoring as soon as possible the supply to the customers. As an example, the description of a procedure currently implemented in France can be found in [32].

2.2.4 Utilisation side

Depending on the type of customer, in case of either lack of supply (i.e., emergency state) or voltage/frequency that do not meet the requirements, backup systems are used for guaranteeing the characteristics requested by the user for the correct operation (e.g., hospital, large industrial site and so on).

2.3 Dimension 3: Operation of the system

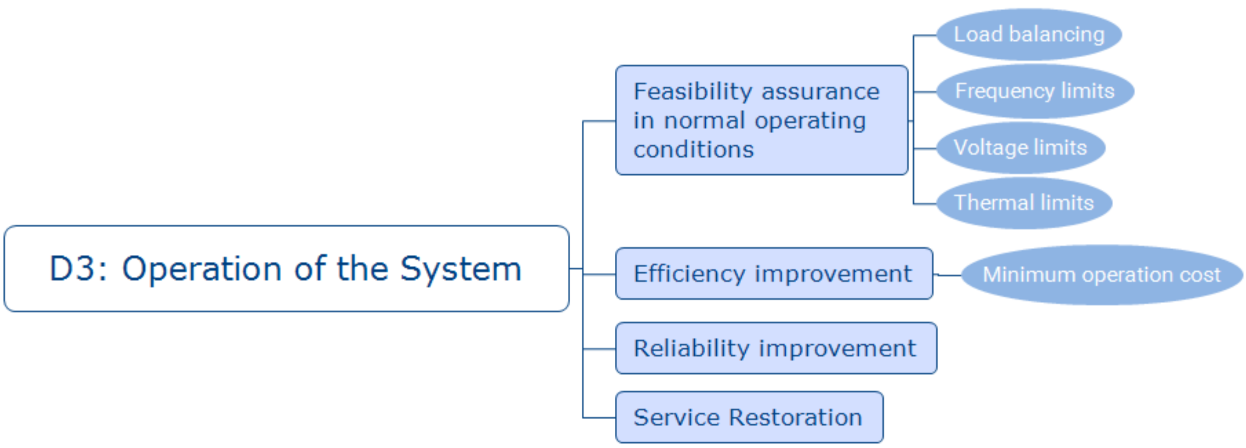


Figure 2-9: Mind map of the Operation of the System operation

2.3.1 Feasibility assurance in normal operating conditions

2.3.1.1 Generation/Transmission

1) Load balancing through dispatching of generation [33]

The total installed power plant capacity is higher than the total electricity demand, and hence the decision about which units can operate has to be made with non-discriminatory criteria by the independent system operator. Such kind of selection of power plants for generation is called *dispatching*

2) Frequency limits

For the absence of reliable and economic storage, active power in the ES has to remain in balance, which means that the power generation has to follow the load curves (and compensate the system losses) continuously. The system operator is responsible to keep active power in balance with respect to network constraints (voltage limit and maximum capacity of the transmission lines). Increasing the penetration of renewable generators with variable outputs might hinder the power system balance control [34].

Generally, balance management in power systems occurs through three consecutive steps known as primary control, secondary control, and tertiary control.

I) Primary control

Primary control maintains the balance between generation and demand in the network using turbine speed governors (i.e., by varying the rotation speed of the turbine and thus of the generator).

In [35], the following definition is suggested:

"Primary control is an automatic decentralised function of the turbine made thanks to the installation on each generator of the primary controller. It is a decentralised/locally installed control equipment for a generation set to control the valves of the turbine based on the speed of the generator (for synchronous generators directly coupled to the electric system frequency). The insensitivity of the primary controller is defined by the limit frequencies between which the controller does not respond. This concept applies to the complete primary controller-generator unit. A distinction is drawn between inadvertent insensitivity associated with structural inaccuracies in the unit and a dead band set intentionally on the controller of a generator."

The power that can be automatically deployed by the primary controller in response to a frequency deviation (both in positive and in negative) is called primary control range. If either the positive or the negative part is only considered, this portion is called primary control reserve.

The primary control is activated within seconds.

Thanks to the use of the primary control, the balance between load and generation is re-established, and the frequency value lies in the admissible range. However, when the value of the area frequency is not the imposed one (in Europe 50 Hz), the secondary control has to be run.

II) Secondary control

In [35], the following definition is suggested:

"Secondary control is a centralised automatic function to regulate the generation in a control area based on secondary control reserves in order to maintain its interchange power flow at the control program with all other control areas (and to correct the loss of capacity in a control area affected by a loss of production).

At the same time, in case of a major frequency deviation (particularly after the loss of a large generation unit) the secondary regulation aims to restore the frequency to its set value in order to free the capacity engaged by the primary control (and to restore the primary control reserves)”.

Secondary control is applied to a selected generator set, by varying their power production.

The power that can be deployed automatically by the secondary controller (both in positive and in negative) is called secondary control range. If either the positive or the negative part is only considered, this portion is called primary control reserve.

Secondary control operates for periods of several minutes, and is therefore dissociated from primary control.

The secondary reserve has to be re-established. For this reason a further regulation level has to be added, called tertiary regulation.

III) Tertiary control

By following [35], “tertiary control is any (automatic or) manual change in the working points of generators (mainly by re-scheduling), in order to restore an adequate secondary control reserve at the right time. The power which can be connected (automatically or) manually under tertiary control, in order to provide an adequate secondary control reserve, is known as the tertiary control reserve or minute reserve. This reserve must be used in such a way that it will contribute to the restoration of the secondary control range when required”.

The restoration of an adequate secondary control range may take, for example, up to 15 minutes, whereas tertiary control for the optimisation of the network and generating system will not necessarily be complete after this time.

For the sake of clarity, Table 2-6 shows the timing of the reserve according to UCTE.

Table 2-6: Timing of reserve according to UCTE [36]

Type of control reserve	Time for initial response	Time of full activation	Time to remain
Primary control reserve	Immediate	< 30 s	≥ 15 min
Secondary control reserve	< 30 s	< 15 min	As long as required
Tertiary control reserve	No recommendation	A short time	No recommendation
Primary control reserve	Immediate	< 30 s	≥ 15 min

3) Voltage limits

For maintaining an acceptable voltage profile, it is necessary to perform some control actions indicated as “voltage control actions” [37]. This is achieved by balancing of the respective reactive power requirements of the network and the customers.

The voltage control is reached in an automatic way by acting on the generation node, at the end nodes or on the nodes of the AC lines or High-Voltage DC lines, on transformers, or other means such that the set voltage level is maintained [28].

The continuously acting automatic equipment controlling the terminal voltage of a synchronous power generator is called Automatic Voltage Regulator (AVR). It compares the actual terminal voltage with a reference value, controlling the output of an excitation control system.

4) Thermal limits

Thanks to phase shifters installed in the transmission network, it is possible to modify the power flow in the network in case of an overloading condition. As extreme ratio, a cut of load/non-dispatchable generation can be performed.

2.3.1.2 Distribution

The distribution system has been designed as a passive system, without any generator connected to it.

For this reason, the only control performed was on the voltage, with the tap-changers installed in the HV/MV and MV/LV transformers. Nowadays, the presence of distributed generation can create some troubles that have to be solved [38].

For the frequency, the distribution system is dependent on the transmission system, and no active control is performed.

Because of the scheme protection, the reverse power flow (i.e., the flow from the customer to the transmission system) should be avoided . Due to the presence of distributed generation or storage in the local system, the reverse power flow could exist, but the number of hours in which it is present and its magnitude have to be limited as much as possible.

2.3.1.3 Utilisation

In normal operation, users have as goal the minimisation of the energy withdrawn from the network, and the maximisation of the potential auto-production coming from its own generators (e.g., supplied by solar energy).

2.3.2 Efficiency improvement

The efficiency improvement is a common goal of all systems, even though this problem is not fundamental for transmission systems because of the high voltage in these systems.

In a distribution system, the DSO operates for minimising the operation costs of the network (mainly caused by power losses) throughout the network, by maintaining a configuration useful also in case of fault. Some switches are remotely controlled (placed in strategic substations), and the normal topology is chosen also for allowing a fast fault location, such that the successive supply restoration can be made in a reasonable time.

2.3.3 Reliability improvement

For improving the reliability of the system, maintenance is fundamental. For this reason, all the systems have to follow proper maintenance plans.

2.3.4 Service restoration

In general, when a fault happens, it has to be solved as fast as possible.

The best strategy has to be studied preventively, by performing simulations of the system highlighting critical situation [26].

2.4 Dimension 4: Time frame

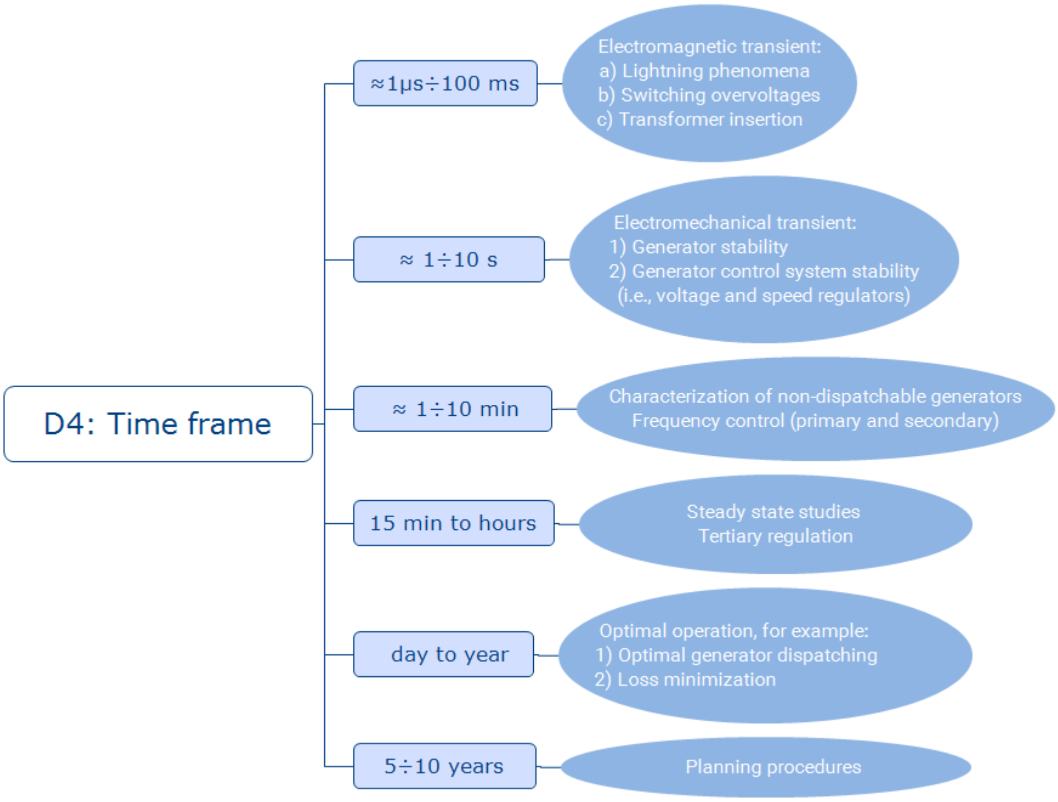


Figure 2-10: Mind map of the Time frame

For the operation of the electricity system, different time frames can be considered [39]:

1) Time frame ≈ 1 µs–100 ms: requested for electromagnetic transients, which implies the description of the behaviour of non-linear components, such as capacitors and inductors. In this category applications are overvoltages, both caused by lightning (≈ 1 µs) and manoeuvres on switches and circuit breakers (≈ 100 µs–10 ms), fault analysis and non-linear phenomena, such as the transformer insertion (≈ 10–100 ms).

2) Time frame ≈ 1–10 s: requested for electromechanical transients, when the aim is the study of the rotational speed of the generators. This study allows both the investigation of the generator stability (loss of synchronisation with the rest of the network) and the stability of the generator control systems (i.e., voltage regulators and speed regulators).

3) Time frame ≈ 1–10 minutes: requested to characterise very precisely the behaviour of the non-dispatchable units and the dynamics of the ES. The applications that can be studied in this time frame are related to the system control (i.e., primary and secondary frequency control) and to the control action on power generators (e.g., output variation).

4) Time frame 15 minutes to hours: requested to characterise most of the loads and the generation units for quasi-steady state studies, and the tertiary regulation.

5) Time frame day to year: requested for studying the optimal operation of the system (e. g., dispatching and losses minimisation).

6) Time frame 5–10 years: requested for planning purposes.

2.5 Dimension 5: Markets

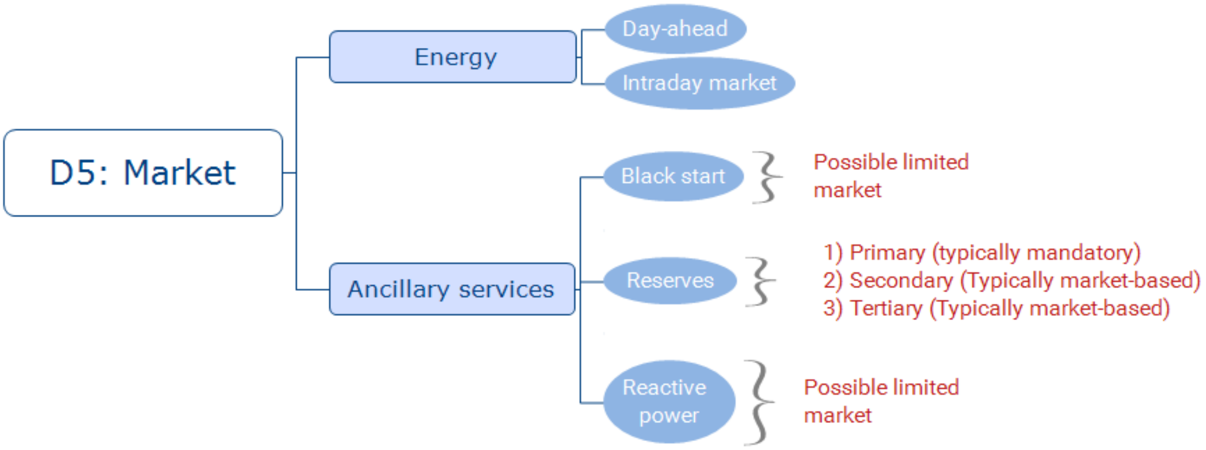


Figure 2-11: Mind map of electricity markets

2.5.1 Energy markets

In a restructured electric power system, electrical energy is traded as a commodity in the electricity market, which in turn fosters open access to all suppliers of electric power, eliminates discrimination against any user of the transmission system, fosters the competitive wholesale market with reduced prices, and encourages competition at the demand side by organizing competitive retail markets [40]. In the electricity market, electrical power and energy are procured to meet the consumers' demand. Electrical energy can be traded in *day-ahead market* or *intraday market* depending on the time frame between transaction and physical electricity delivery.

1) Day-ahead market

The day-ahead market is a market area for trading power for the next day. The market price is related to each hour of the next day, and it is based on the generators' energy offers (to produce) and consumers' energy bids (to consume) registered to the market [41].

2) Intraday market

The intraday market is an electricity market (supplementing the day-ahead market) for trading the difference between scheduled power and updated forecasts after the closure of the day-ahead market and before the delivery time in the next day [41].

2.5.2 Ancillary services

The term "ancillary services" refers to a range of functions procured by Independent System Operators (ISOs) for keeping a balance between supply and demand, stabilising the transmission system and maintaining the power quality on an economical basis in competitive electricity markets [42]. Ancillary services include *black start capability* (the ability to restart a grid following a blackout), *spinning* and *non-spinning* reserves (mainly primary and secondary reserves), and *reactive power support*.

Generally, ancillary services can be provided through two main mechanisms, i.e., either *compulsory* or *contractually/market based*. However, their provision is usually achieved through a competitive market, which is oriented to maximise participation and minimise costs [43]. Due to the importance and technical characteristics of some services like reactive power support, they usually are procured as compulsory services with limited financial compensation mechanisms.

1) Black start

Black Start is the procedure to recover from a total or partial shutdown of the transmission system causing an extensive loss of supplies. It is provided by generators that can self-start without requiring power from the grid [44], for example hydro power plants. The isolated portions of the transmission system are started individually and are gradually reconnected to each other in order to form an interconnected system again.

2) Reserves

Operating reserves in power systems are able to provide the additional capacity (generation and responsive load availability) that potentially can be called in case of load increases or generation decreases, due to the unpredictability or variability of the operative conditions. The available reserve can be either on-line or in standby, for assistance in restoring the active power balance [45].

The provision of primary reserve used to be mandatory both in Nordic and UCTE countries. During recent years, however, agreements including economic compensation have become common.

There are two main options for providing secondary reserve, including bilateral contracts between the ISO and the provider, and commercial services or organized markets.

In some countries the primary reserve is even traded commercially. For example, in Germany, there are half-yearly auctions for primary and secondary control capacity. In Poland, primary and secondary reserves are purchased in accordance of bilateral agreement on the obligatory basis. However, tertiary reserves in both countries are purchased through competitive markets [46].

3) Reactive Power

Reactive power service is the injection or withdrawal of reactive power to keep the system voltage within prescribed levels at various points in the transmission grid, and to compensate for the reactive requirements of the grid [47]. It should be noted that reactive power management and voltage control are the same ancillary service [48].

3 Present and perspective applications of PtG in the ES

By referring to the structure of the ES, this section aims both to present a survey of the applications suggested in literature (e.g. [14]), and to suggest new ones, for opening new perspectives and research topics.

3.1 Electricity generation

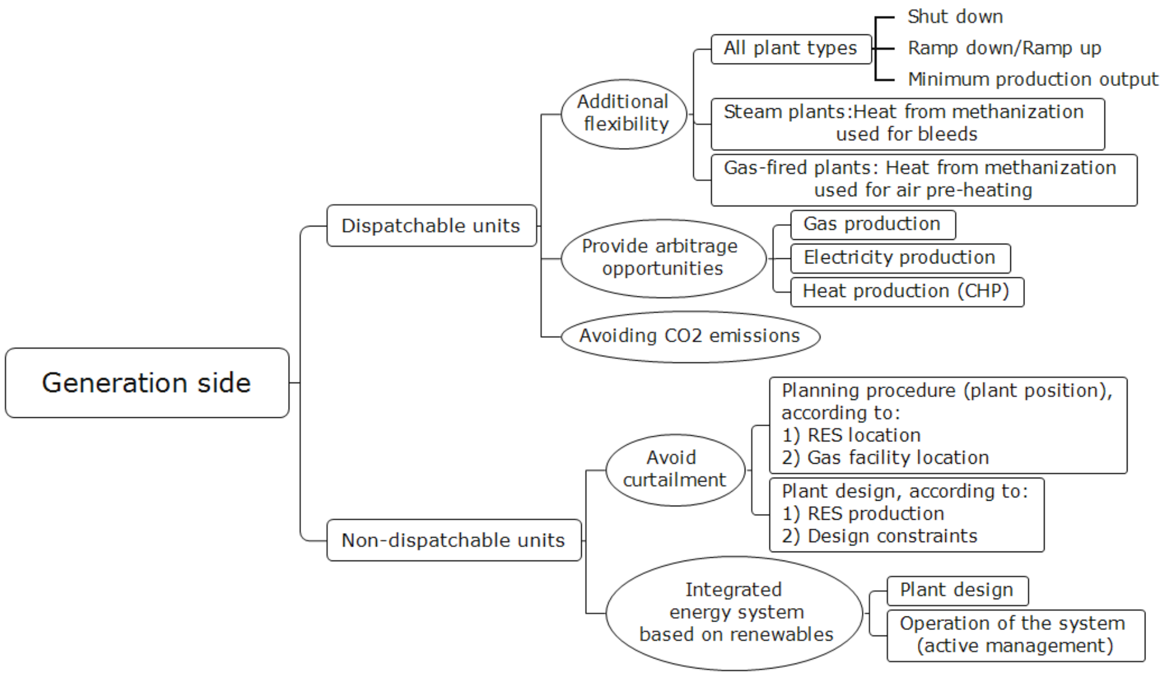


Figure 3-1: PtG applications to the generation side [14].

Figure 3-1 indicates the potential applications of PtG on the electricity generation side. First of all, the possible applications change according to the type of generators considered, i.e., dispatchable and non-dispatchable units. The common aim for both units is the improvement of the efficiency of the plant, both from a technical and economic point of view.

By considering dispatchable units, PtG can provide:

- More flexibility: due to the possible shift from electricity to gas and vice-versa [49], it is possible to mitigate all the problems created by variations in the injected and withdrawn electrical power.
- Arbitrage opportunity: considering the economic terms associated to the provision of services through a system that may be supplied either by fuel or power [50].
- CO_2 emission reduction, because the balance of the RES production can be made with a gas turbine fed by SNG.

On the other hand, PtG associated to non-dispatchable units can be useful for:

- Reducing the renewable energy curtailment
- Introducing an RES-based integrated energy system

For each point, both the state of the art and new proposals are reported in the following section.

3.1.1 Dispatchable units

The use of PtG associated with dispatchable units has been studied in some papers, suggesting several possible applications.

An application involving a French nuclear power plant and PtG is shown in [51]: the use of PtG allows to maintain the production as flat as possible, allowing a better exploitation of the nuclear power plant.

In [52], the authors present a study regarding the economic feasibility of a biomass-fired CHP integrated with PtG. The biomass plant has a size of 300 MW, and the paper presents some aspects of the methanation process modelled in a simplified way. It is worth to note that the paper considers also the production of oxygen. Another application regarding biomass and PtG is reported in [53], where an innovative PtG-biomass oxyfuel hybrid system is shown.

The comparison between two SNG plants integrated with Carbon Capture (CC) systems is reported [54], by focusing on the design of the process part.

Some potential applications of PtG involving dispatchable power plants[5] are presented in section 5.

3.1.2 Non-dispatchable units

The plants exploiting renewable energies are mostly[6] non-dispatchable, because the production cannot be controlled by the system operator [55][56]. Thus, the reduction of the curtailment of the energy produced by RES is becoming fundamental to guarantee a sustainable energy system [1], and for reaching this goal the use of storage technologies is fundamental [57][58]. The improvement of the dispatchability of wind turbines and its economic evaluation are the topics investigated in [59]. In particular, the paper considers only the production of H_2 for feeding a gas turbine, but a natural upgrade with a methanation step could be possible, and the entire facility would feed the turbine with SNG.

In case of isolated systems (such as an island), the reduction/elimination of the RES curtailment becomes much more important. An example regarding Ireland has been reported in [60]. The source of CO_2 considered more suitable in the paper is provided by biogas plants, and the installation of PtG can decrease the Irish energy curtailment.

The study in [61] shows the use of PtG for producing SNG in Spain. The authors present both the design of the process and an economic assessment (by considering the costs of electricity and gas).

The study reported in [62] analyses the photovoltaic (PV) plant coupled with storage. Two technologies have been considered, i.e., batteries and hydrogen. As a result, the paper emphasises the necessity to make detailed analysis about the case under study, for highlighting the profitability

[5] The power plant considered in this report is a Combined Heat and Power (CHP) plants, for which the heat represents an operation constraint.
[6] "Mostly" means that not all RES power plants are non-dispatchable; a hydroelectric power plant is an example of a dispatchable RES-based power plant

to install the storage. Indeed, this particular case presents negative profitability due to the high cost of the electrolyser.

New applications of PtG with non-dispatchable plants should consider external constraints (related, for example, to the gas network), as well as a model of the PtG facility as close as possible to the real one, possibly by considering also the relevant dynamics.

3.2 Electricity transmission

In Figure 3-2 the overview of applications of PtG in the transmission system is shown. Three main activities have been found, i.e., ancillary services, energy storage/RES integration and system management. A detailed explanation of every activity is reported in the following sections.

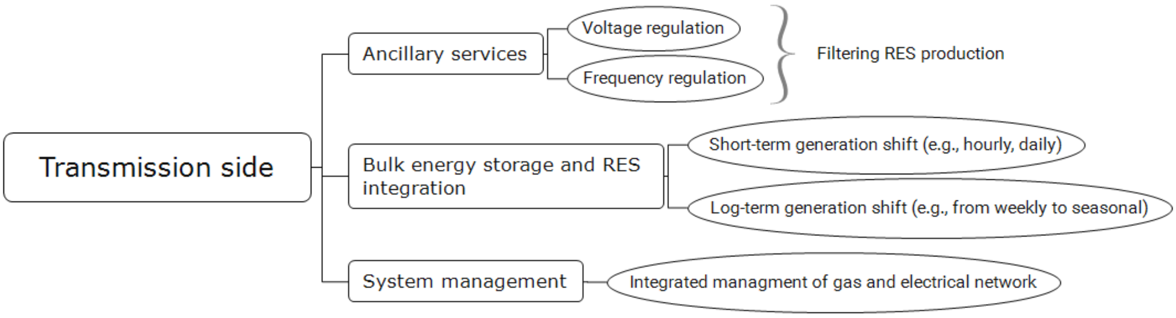


Figure 3-2: PtG applications on the electricity transmission side [14]

3.2.1 Ancillary services (filtering RES production)

The interface between PtG and the grid is made by means of the electrolyser: this fact leads to considering the dynamics of the electrolyser as the main aspect for providing ancillary services by exploiting PtG. Hence, in this framework the dynamics of the production of SNG is not considered. This fact implies that the papers present in literature do not consider PtG with production of SNG as a possible means for providing ancillary services to the network.

Grid ancillary services can be categorized with respect to their duration, as presented in [7], i.e., very short (from milliseconds to 5 min), short (5 min to 1 hour), intermediate (1 hour to 3 days) and long duration (seasonal). The hydrogen produced coupled with a fuel-cell plant and a hydrogen tank could substitute the traditional power plants either for the spinning reserve, or as source for a black start (both with short duration). The exploitation of the produced hydrogen could be successful used in intermediate services, such as:

- load following (i.e., a continuous service provided for matching load and generation [63]);
- load levelling (allowing a load as uniform as possible [63]);
- unit commitment (for covering the mismatch between the forecast of renewable production and the real one, if this mismatch is due to different weather conditions over several hours [64]).

In [16] some cases are presented in which PtG can provide voltage and frequency regulation. In this line, recent news reported in [65] have shown response time compatible with the frequency regulation (800 ms for turn on and 140 ms for turn off), which indicated the technical possibility to use PtG as RES filter.

3.2.2 Bulk energy storage and RES integration

The increase of the flexibility of the system is one of the main interests for the proper management of the ES [6]. In [66], the author investigates both power-to-liquid and PtG for getting a strong integration of RES in the German transmission system.

A study of load-levelling applications considering an economic analysis based on the revenue of the storage plant is reported in [67]. The study remarks that PtG is only remunerative in seasonal storage applications, with other technologies (such as pump hydro plants) being more adapt for daily load levelling.

The interest regarding PtG is demonstrated in [68], where this technology is remarked as one of the fundamental technologies for reaching a 100% RES-based system in northeast Asia.

In [69], the authors investigate the overall cost reduction of the ES, by indicating PtG as the third more suitable technology, after pumped hydro storage (PHS) and compressed air energy storage (CAES).

In [70], the authors propose a comprehensive model of the German energy sector, which considers PtG to be one of the technologies allowing for handling electricity and heat together.

In [71], the authors study the power balance of the Baltic region in presence of large wind power generation. The methanation of biogas implies more wind production than what can be used at a given moment, and its exploitation can reduce both the import of fossil fuel and electricity.

The installation of PtG can provide a variation of the power plants dispatch. For example, in [72] different PtG plants are installed in different points of the simplified Danish transmission network. The wind curtailment can be reduced by using PtG, and also the duration of the congestion is reduced. As simplification, no connections with neighbour countries are considered, and it is remarked that by considering it, the worth of installing PtG could possibly reduce.

In [73] the authors show that PtG may allow integrating the excess of renewables in a 85%-RES based German system, by passing from 70 TWh/year to 30 TWh/year.

3.2.3 Integrated management of electrical and gas networks

By considering the developed countries, gas and electricity infrastructure are always present. Their joint analysis [74] opens the possibility of new applications and benefits.

In [75], the authors analyse how the prices of electricity and gas change due to the transfer limits of the gas grid and electrical grid. The model provides as output the optimum electricity production cost and gas cost when the two energy vectors have to satisfy a demand level.

Another example of joint analysis is offered in [76]. By supposing the presence of large PtG facilities (i.e., 1 GW), both the production of SNG and H_2 are considered for alleviating gas network congestions. The variation of the cost of natural gas due to the joint presence of production of SNG and storage facility (leading to a gas demand reduction) is studied in [77].

The study presented in [78] considers a model of gas and electrical systems, together with the carbon dioxide-related sector, and shows the possibility of PtG to link all the sectors, as well as that its installation is capable to modify the price of gas and electricity (if PtG is the gas marginal unit).

Other approaches aiming at the unified handling of both gas grid and transmission grid are presented in [79] [80] [81]. In particular, the study [79] focuses on the available transfer capacity of the transmission system by considering the constraints of the gas network as well. It is worth to note that possible outages in the ES are possible due to the constraint on gas networks, which block the supply of gas-fired plants. In [80], the authors show that the joint presence of PtG and gas-fired power plants is able to reduce the power losses and to reduce the consumption for gas compression. The study presented in [81] remarks that the study of the gas flow equation cannot be linearized in a simple way and suggests a new methodology for overcoming this issue.

3.2.4 Congestion management

Due to the connection of large RES plants, the ES may incur congestions [5]. This fact leads to the cutting of energy production, and for overcoming this issue the installation of storage facilities is requested (such as batteries, as the ones installed by the Italian TSO [82]).

Different options in a network characterised by a large number of congestions are evaluated in [58]. Both transmission and distribution network are considered, and the results show that using the storage only for solving the energy curtailment is not convenient due to the large investment costs and the low utilisation of the storage facilities.

3.2.5 Perspective applications

In this framework, an adequate model of the bulk system with different scales (regional, country, Europe) should couple with a realistic PtG model, both in terms of size and dynamics. The constraints due to the gas network and the CO_2 availability should be considered as well. The creation of hybrid systems could offer the best answer for handling both short and long-term energy requests [83].

3.3 Electricity distribution and utilisation

3.3.1 Existing analysis of the integration of PtG facilities

The distribution system was born as a passive network, i.e., the energy always flowed from generation to customers. With the introduction and the widespread use of RES-based plants (together with storage and demand response resources [84]), the energy flow is often reversed, and goes from the customer towards the connection point between transmission and distribution networks.

In [85], the installation of PtG facilities in a region with large solar energy penetration is studied. The analysis remarks that it is possible to absorb about 20% of the excess of solar energy by installing PtG facilities (the time period considered lies in 2015–2025).

As mentioned in Section 3.2.4, source [58] reports a study related to a distribution network with a large occurrence of congestion due to RES-based power plants. Also in this case (as for the transmission system), the recovered energy does not justify the investment cost.

The control of the distribution system, now, is not as advanced yet as the one in the transmission system. However, a new approach based on active control of the network is undergoing. An example of this type of approach is reported in [86].

A planning of PtG in HV and MV networks is shown in [87], whereas the siting and sizing of PtG facilities in a MV network is shown in [88]. In the first paper, the economic function is a sum of different objectives, whereas in the latter one it is the combination of power losses and a number of PtG facilities.

In [89], the authors present a non-linear predictive control model aiming to optimise the management of the LV distribution, the gas network and heat systems. In this way, the power flowing through the MV/LV transformers is minimised.

By considering the utilisation side, a lot of publications consider the use of hydrogen at the customer level [90], but no specific application regarding the use of methanation has been found.

3.3.2 Perspective applications

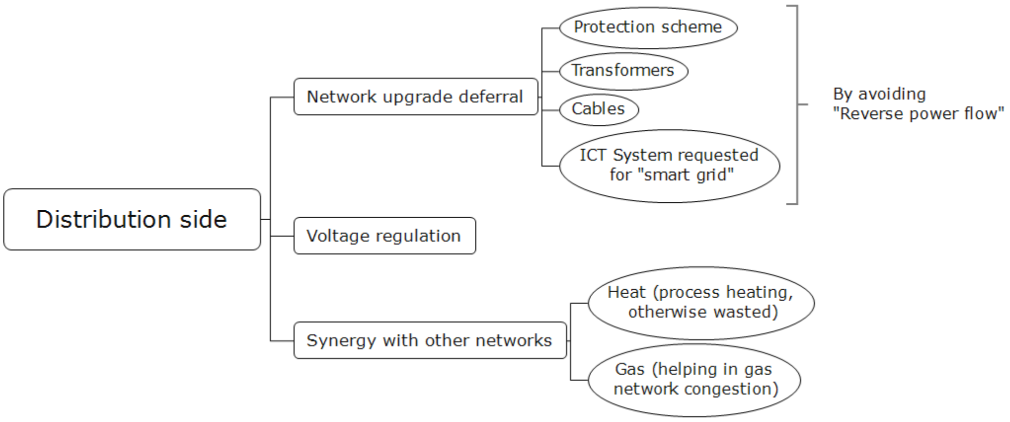


Figure 3-3: PtG applications on the electricity distribution side [14]

As shown in Figure 3-3, one the most promising applications is the network upgrade deferral. In distribution networks where a large amount of RES is installed, the reverse power flow may be quite continuous, and the change of transformers and protection schemes, substitution of transformers, together with the implementation of communication infrastructure (necessary for “smart” devices), have a cost. For this reason, the evaluation of how much storage facilities such as PtG can alleviate the problem, and getting the cost for this, is interesting for planning future actions on the grid.

On the other hand, if the perspective is the implementation of a “smart network”, the introduction of a real time control system may be implemented (with the use of a real time controller and smart metering).

A further field to be explored are the synergies among different energy sectors, and in this sense PtG can have a key role for its cross-sector nature. The coupling of different systems can lead to improve the operation of all the infrastructures under analysis. Bidirectional conversion can be made by exploring together PtG and a small size gas-fired turbine.

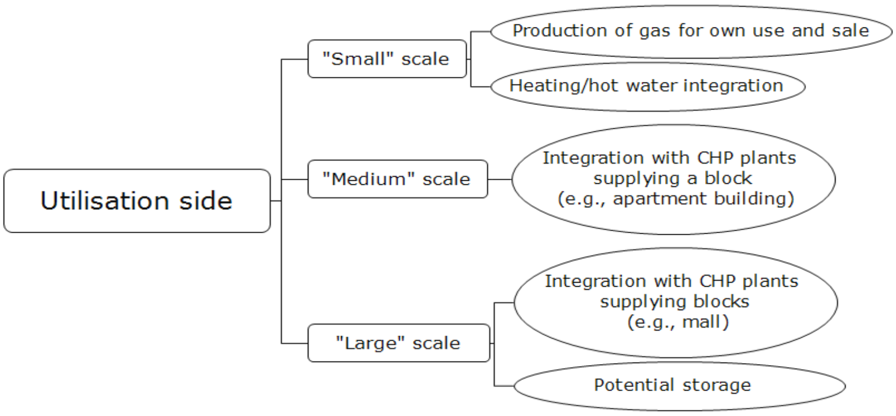


Figure 3-4: PtG applications on the electricity utilisation side [14]

As matter of suggestion, Fig. Figure 3-4 reports some applications that could be interesting.

By considering the size of the customers (small, medium, and big) and the excess of RES production, the following applications can be thought of:

- Small size (e.g., size related for example to bifamiliar houses sharing private facilities, like the courtyard, the heating system, and so on). An application can be the production of SNG both for self-consume and sale, by integrating heating and hot water as well (thanks to the waste heat from the methanation).
- Medium size (e.g., apartment building), with possible installation of a small CHP that can be coupled with the PtG.
- Large size (like a mall), where besides the applications listed for the two other sizes, a further application is the production of car fuel, for being sold or exploited for the company cars.

It is worth to note that if electricity comes from the market, the application of PtG could be probably not convenient, because it is not possible to recover the investment costs (due to the small spread between electricity and gas costs [91])

4 Categorizing PtG applications found in literature

This section aims to classify the PtG applications found in literature (presented in Section 3) by using the five dimensions composing the general framework presented before.

Table 4-1 shows as a summary the number of publications in every system subdimension, based on the characterisation reported in Table 4-2

- Dimension D1: System Structure

  The applications found in literature mainly refer to the application of PtG for the management of the transmission system in case of excess of RES (16 papers). The remaining cases analyse the coupling of PtG with generation plants (6) and the applications of PtG in distribution systems (6). No application considering PtG (interpreted as power-to-methane) in the utilisation sector has been found.

- Dimension D2: State of the System

  All applications analysed are related to the Normal operation conditions of the electrical system. This fact is justified by the relatively new nature of the technology, which is still under development, and it is not clear how the technology can improve the performance of the main system when it operates in critical conditions.

- Dimension D3: Operation of the system

  The use of PtG in the analysed applications is devoted to assure the feasibility of the system in normal conditions.

  From this fact it is evident that the analyses carried out so far are related to the coupling of PtG with present network assets, and not the use of it for improving the current performance of the systems or for reliability/restoration aims.

- Dimension D4: Time frame

  The time frame mainly used in the analysed applications refers to 1 day to a year (20 papers), because most of the applications are related to the analysis of the system in steady state conditions of the electrical systems.

  However, one publication (i.e., [65]) reports the potential performance of a new electrolyser, claiming the possibility to have a time response in the order of ≈ 100 ms.

  Other papers consider as time framework 15 minutes to 1 hour (3 papers) and only one reports an application with a time frame 1–10 minutes.

- Dimension D5: Market

  Due to the applications presented, most of the papers use the day-ahead market as framework (24 papers), while only four publications present the possible use of PtG in the market of ancillary services.

Table 4-1: Number of papers per system subdimension

Dimensions	Sub-dimensions	#papers
D1 System Structure	D1.1 Generation	6
	D1.2 Transmission	16
	D1.3 Distribution	6
	D1.4 Utilisation	0
D2 State of the System	D2.1 Normal	28
	D2.2 Alert	0
	D2.3 Emergency	0
	D2.4 Extremis	0
	D2.5 Restoration	0
D3 Operation of the System	D3.1 Feasibility assurance in normal operating conditions	28
	D3.2 Efficiency improvement	0
	D3.3 Reliability improvement	0
	D3.4 Service restoration	0
D4 Time Frame	D4.1 ≈ 1 μs–100 ms	1
	D4.2 ≈ 1–10 s	0
	D4.3 ≈ 1–10 min	1
	D4.4 ≈ 15 min–hours	3
	D4.5 ≈ 1day to year	20
	D4.6 ≈ 5–10 years	3
D5 Market	D5.1 Energy	24
	D5.2 Ancillary services	4

Table 4-2: Characterisation of PtG applications by type

Application	D1 System Structure				D2 State of the system					D3 Operation of the system				D4 Time frame						D5 Market		Source
	D1.1 Generation	D1.2 Transmission	D1.3 Distribution	D1.4 Utilisation	D2.1 Normal	D2.2 Alert	D2.3 Emergency	D2.4 Extremis	D2.5 Restoration	D3.1 Feasibility assurance in normal operating conditions	D3.2 Efficiency improvement	D3.3 Reliability improvement	D3.4 Service Restoration	D4.1 ≈ 1 µs–100 ms	D4.2 ≈ 1–10 s	D4.3 ≈ 1–10 min	D4.4 ≈ 15 min – hours	D4.5 ≈ 1day to year	D4.6 ≈ 5–10 years	D5.1 Energy	D5.2 Ancillary services	
Utilisation excess of nuclear power plants	X				X					X									X	X		[51]
Economic evaluation of PtG plant coupled with CHP	X				X					X						X					X	[52]
Increase of the economic revenue by improving wind production uncertainty	X				X					X							X				X	[59]
Reducing RES curtailment by using PtG in islands	X				X					X								X		X		[60]
Application of PtG with production of electricity from SNG	X				X					X								X		X		[61]

Application	D1 System Structure				D2 State of the system					D3 Operation of the system				D4 Time frame						D5 Market		Source
	D1.1 Generation	D1.2 Transmission	D1.3 Distribution	D1.4 Utilisation	D2.1 Normal	D2.2 Alert	D2.3 Emergency	D2.4 Extremis	D2.5 Restoration	D3.1 Feasibility assurance in normal operating conditions	D3.2 Efficiency improvement	D3.3 Reliability improvement	D3.4 Service Restoration	D4.1 ≈ 1 µs–100 ms	D4.2 ≈ 1–10 s	D4.3 ≈ 1–10 min	D4.4 ≈ 15 min – hours	D4.5 ≈ 1day to year	D4.6 ≈ 5–10 years	D5.1 Energy	D5.2 Ancillary services	
Presentation of dynamic performance of ITM power		X			X					X				X							X	[65]
Economic assessment of storage technologies for load levelling		X			X					X								X		X		[67]
Analysis of a 100%-RES supplied energy system		X			X					X								X		X		[68]
Unit commitment with different wind penetration and storage		X			X					X								X		X		[69]
Analysis of electricity grid and heat sector	X				X					X								X		X		[70]
Analysis of PV plant coupled with storage		X			X					X								X		X		[62]
Application of PtG with production of electricity from SNG	X				X					X								X		X		[61]

Application	D1 System Structure				D2 State of the system					D3 Operation of the system				D4 Time frame						D5 Market		Source
	D1.1 Generation	D1.2 Transmission	D1.3 Distribution	D1.4 Utilisation	D2.1 Normal	D2.2 Alert	D2.3 Emergency	D2.4 Extremis	D2.5 Restoration	D3.1 Feasibility assurance in normal operating conditions	D3.2 Efficiency improvement	D3.3 Reliability improvement	D3.4 Service Restoration	D4.1 ≈ 1 μs–100 ms	D4.2 ≈ 1–10 s	D4.3 ≈ 1–10 min	D4.4 ≈ 15 min – hours	D4.5 ≈ 1day to year	D4.6 ≈ 5–10 years	D5.1 Energy	D5.2 Ancillary services	
Analysis of production of CH_4 based on excess of RES in Baltic region		X			X					X								X		X		[71]
Implementation of PtG facilities under different scenarios taking into account transmission network constraints and gas infrastructure		X			X					X								X		X		[72]
Analysis of the impact of PtG in presence of 85% RES in Germany, including a comparison with other technologies		X			X					X								X		X		[73]
Analysis of the interaction between electrical grid and gas grid considering transmission network constraints		X			X					X								X		X		[75]
Joint analysis of electrical and gas network		X			X					X								X		X		[76]

Application	D1 System Structure				D2 State of the system					D3 Operation of the system				D4 Time frame						D5 Market		Source
	D1.1 Generation	D1.2 Transmission	D1.3 Distribution	D1.4 Utilisation	D2.1 Normal	D2.2 Alert	D2.3 Emergency	D2.4 Extremis	D2.5 Restoration	D3.1 Feasibility assurance in normal operating conditions	D3.2 Efficiency improvement	D3.3 Reliability improvement	D3.4 Service Restoration	D4.1 ≈ 1 µs–100 ms	D4.2 ≈ 1–10 s	D4.3 ≈ 1–10 min	D4.4 ≈ 15 min – hours	D4.5 ≈ 1day to year	D4.6 ≈ 5–10 years	D5.1 Energy	D5.2 Ancillary services	
Joint analysis of electrical and gas network, by considering the effect of the production of SNG on gas price		X			X					X								X		X		[77]
Analysis of the impact of PtG on energy system (considering electricity, CO_2 and gas)		X			X					X								X		X		[78]
Calculation of the available transfer capability of transmission network by considering gas and electrical grid constraints		X			X					X							X			X		[79]
Steady-state analysis of the integrated gas and electric power system		X			X					X								X		X		[80]
Steady-state analysis of the integrated gas and electric power system		X			X					X								X		X		[81]

Application	D1 System Structure				D2 State of the system					D3 Operation of the system				D4 Time frame						D5 Market		Source
	D1.1 Generation	D1.2 Transmission	D1.3 Distribution	D1.4 Utilisation	D2.1 Normal	D2.2 Alert	D2.3 Emergency	D2.4 Extremis	D2.5 Restoration	D3.1 Feasibility assurance in normal operating conditions	D3.2 Efficiency improvement	D3.3 Reliability improvement	D3.4 Service Restoration	D4.1 ≈ 1 µs–100 ms	D4.2 ≈ 1–10 s	D4.3 ≈ 1–10 min	D4.4 ≈ 15 min – hours	D4.5 ≈ 1day to year	D4.6 ≈ 5–10 years	D5.1 Energy	D5.2 Ancillary services	
Storage options for preventing congestions caused by excess of RES at transmission level		X			X					X								X		X		[58]
Storage options for preventing congestions caused by excess of RES at transmission level			X		X					X								X		X		[58]
Implementation of PtG for absorbing surplus of solar power			X		X					X								X		X		[85]
Determination of the optimal siting for PtG technologies			X		X					X									X	X		[87]
Sizing and placement of PtG in distribution networks			X		X					X									X	X		[88]

Application	D1 System Structure				D2 State of the system					D3 Operation of the system				D4 Time frame						D5 Market		Source
	D1.1 Generation	D1.2 Transmission	D1.3 Distribution	D1.4 Utilisation	D2.1 Normal	D2.2 Alert	D2.3 Emergency	D2.4 Extremis	D2.5 Restoration	D3.1 Feasibility assurance in normal operating conditions	D3.2 Efficiency improvement	D3.3 Reliability improvement	D3.4 Service Restoration	D4.1 ≈ 1 µs–100 ms	D4.2 ≈ 1–10 s	D4.3 ≈ 1–10 min	D4.4 ≈ 15 min – hours	D4.5 ≈ 1day to year	D4.6 ≈ 5–10 years	D5.1 Energy	D5.2 Ancillary services	
Active control of the distribution network for controlling the network voltage			X		X					X							X				X	[86]
Non-linear predictive control model for optimizing the LV distribution, the gas network and heat systems			X		X					X								X		X		[89]

5 PtG with dispatchable power plants

This section presents a focus on specific applications involving dispatchable power plants. This choice has been investigated in detail because the analysis of this topic has taken advantage from the expertise of one of the partner involved (IREN), which is currently operating some CHP power plants operating in the electricity market in Italy. Thanks to this, two different issues existing in the current operation of the power plants have been highlighted and hence investigated in combination with PtG facilities, i.e.:

- Unbalance between actual generation and scheduled generation (imposed by TSO), reported in Section 5.1.
- Supporting gas-fired power plant for offering capacity downward, reported in Section 5.2.

The data used are related to a CHP of size 400 MW. The production of heat represents a constraint for the plant itself. From the operation point of view, the CHP works as a CCGT with some operational limits due to the production of heat, and, due to this, in the following section the plant will be always indicated as CCGT.

5.1 Use of PtG for balancing a gas-fired power plant

The interface between the PtG facility and the electricity network is essentially the electrolyser, which represents the fundamental device for studying the performance of the PtG technology in electrical systems. For this reason, Section 5.1.1 introduces the linear model of the electrolyser, obtained from the analysis of real measurement provided by WP 2.

Section 5.1.2 – 5.1.5 aim to present the hypothesis and the results of the study carried out for highlighting the potential of PtG for recovering the power imbalance of a gas-fired power plant.

The expression “power unbalance” is used here for indicating the mismatch between the physical power produced by the power plant (i.e., the production of the CCGT) and the scheduled power, imposed by the transactions on the day-ahead market.

The Transmission System Operator (TSO) can either recognise a benefit to the owner of the power plant, or inflict a penalty at the end of every month. The benefit/penalty depends on the sign of the unbalance (positive if the power plant is producing more than it was established, negative otherwise) and the status of the zone (positive if the zone has an excess of energy production, negative otherwise), and it is proportional to the amount of unbalancing.

5.1.1 Modelling the electrolyser

This section aims to show a model of the electrolyser used for getting insights related to the behaviour of PtG in in the coupling with gas-fired power plant.

For doing that, several measured operation points of the electrolyser operating in Falkenhagen have been used, and successively analysed. In particular, by aggregating the measurement provided by the plant, it has been possible to get a linear characteristic linking the amount of hydrogen produced and the input power of the electrolyser.

Table 5-1 lists the nominal data of the electrolyser, whereas Figure 5-1 shows the linear characteristic used in this report. The scale up of the model can be made by reporting the characteristic in pu and multiplying it by the nominal values of power and hourly hydrogen production.

Table 5-1: Rated data of the electrolyser studied

Nominal power [MW]	2
Rated H_2 production [m^3/h]	360
P_{min} [% P_{nom}]	20%[7]

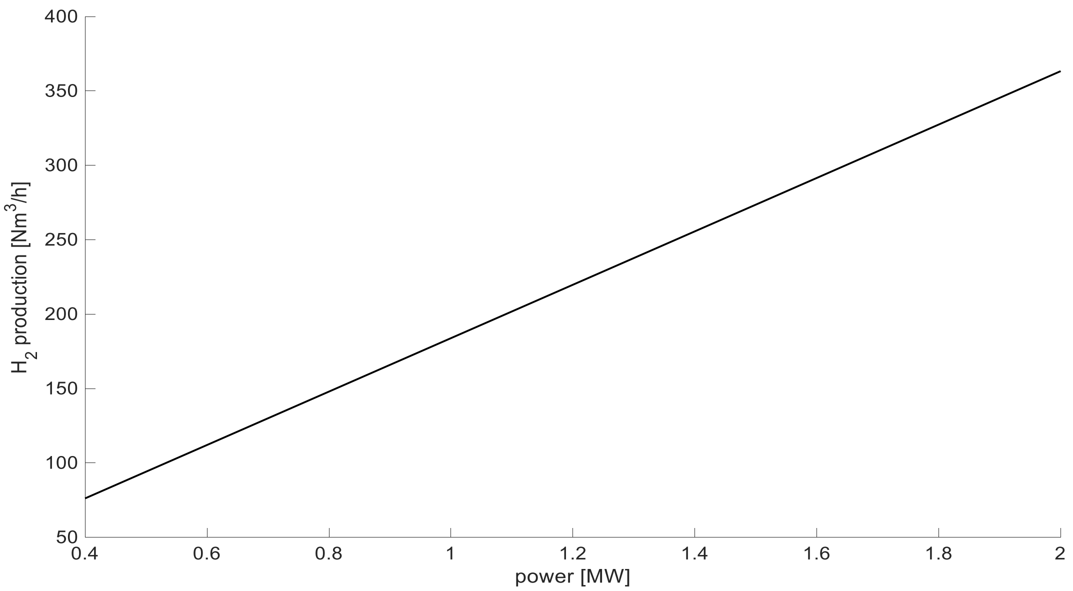


Figure 5-1 : Linear characteristic of the electrolyser.

5.1.2 Modeling the system

The simulations have been based on the conceptual framework shown in Figure 5-2.

[7] The limit is required due to technical reasons, due to the particular layout of the PtG plants considered. In this report, for considering only the limit of the electrolyser, P_{min} = 5% has been chosen [92]

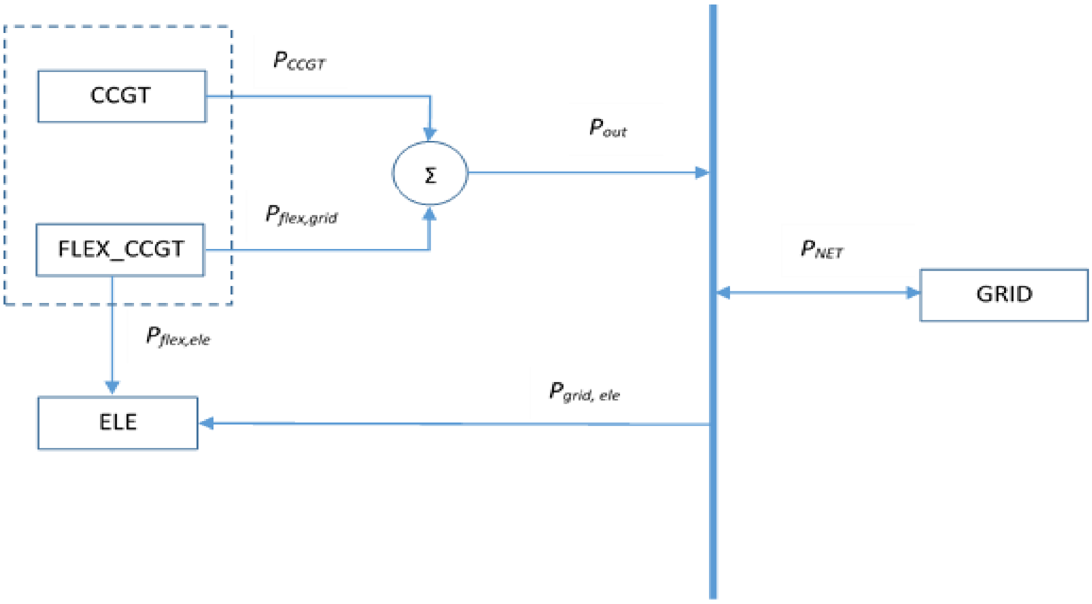


Figure 5-2 : Multi-energy scheme representing the case study.

The block CCGT represents the current power plant, which produces, for every time step, a power P_{CCGT}.

The block FLEX_CCGT represents the additional production that has to be provided by the CCGT for solving the unbalance. The additional production can be either provided to the electrolyser ELE (by means of $P_{\text{flex,ele}}$) or to the grid (by means of $P_{\text{flex,grid}}$).

The total power exchanged between power plant and grid is P_{NET}. The production scheduled is indicated in the following as P_{TSO}.

The summary of the variables is provided in Table 5-2.

Table 5-2 : Summary of the variables

Variable	Description
P_{CCGT}	Actual production of the gas turbine
$P_{\text{flex,grid}}$	Additional portion of electricity delivered to the grid by means of the flexibility of the system (covering negative unbalance)
$P_{\text{flex,ele}}$	Portion of electricity delivered to the electrolyser by means of the flexibility of the system (covering positive unbalance)
P_{out}	Power delivered to the grid by the system CCGT+FLEX
$P_{\text{grid,ele}}$	Portion of network withdrawn by the grid for supplying the electrolyser
P_{NET}	Net power exchanged between power plant and grid

Four different control schemes have been tested. The explanation of each of them is provided in the following.

Control scheme C1

The control scheme is based on the calculation of the mismatch between P_{CCGT} and P_{TSO}, called ΔP, and on an imposed operation point of the electrolyser (called P_{SET}).

The overall diagram is shown in Figure 5-4: the control scheme makes different actions depending on the sign of ΔP and its value.

By introducing the nominal power of the electrolyser, i.e., $P_{\mathrm{nom,ele}}$, depending on the value of the mismatch the control actions are different (as summarised in Figure 5-3):

- CASE A: $\Delta P < 0$
- CASE B: $\Delta P = 0$
- CASE C: $\Delta P \geq 0$ and $\Delta P \leq P_{\mathrm{SET}}$
- CASE D: $\Delta P \geq 0$ and $P_{\mathrm{SET}} < \Delta P < P_{\mathrm{nom,ele}}$
- CASE E: $\Delta P \geq 0$ and $\Delta P \geq P_{\mathrm{nom,ele}}$

Figure 5-3: Value of the mismatch *ΔP* leading to different control actions.

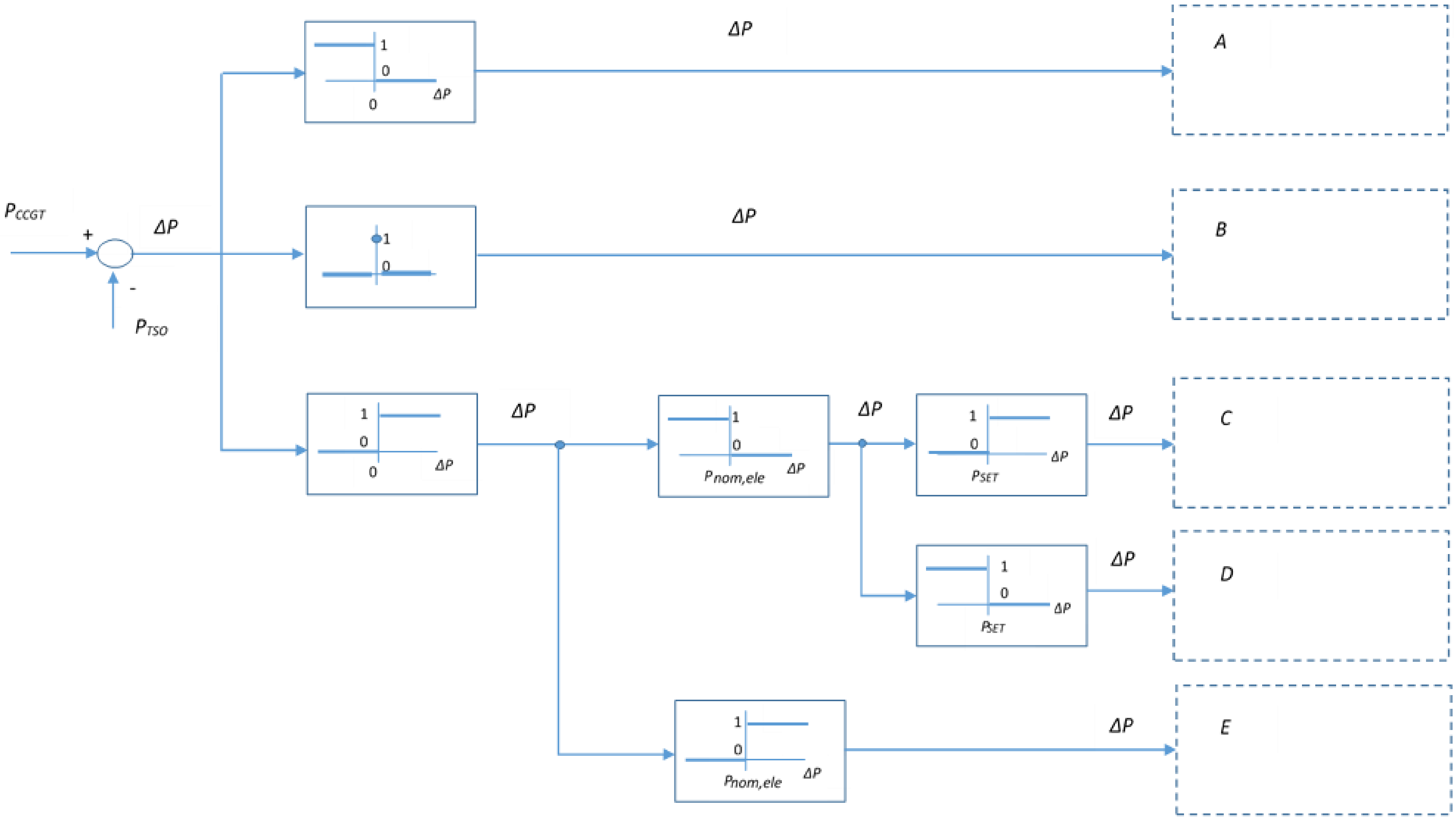


Figure 5-4: Control chain for the different cases .

Case A: $\Delta P < 0$

The control scheme used in Case A is shown in Figure 5-5.

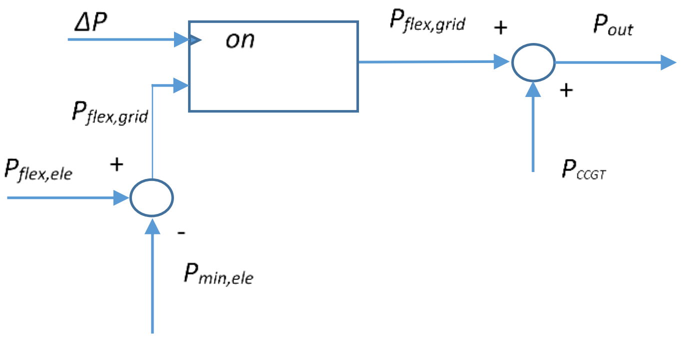


Figure 5-5: Control chain for case A.

The presence of the signal ΔP enables this control part. The mismatch, in this case, is negative and the control aims to cover it partially, by exploiting the present value of power provided by the flexibility to the electrolyser $P_{\text{flex,ele}}$. In fact, the mismatch ΔP is partially covered by the difference between the present value of the flexibility supplying the electrolyser (i.e., $P_{\text{flex,ele}}$) and the minimum value, which has to be guaranteed to the electrolyser (i.e., $P_{\text{min,ele}}$).

Case B: $\Delta P = 0$

The control scheme used in the Case B is shown in Figure 5-6.

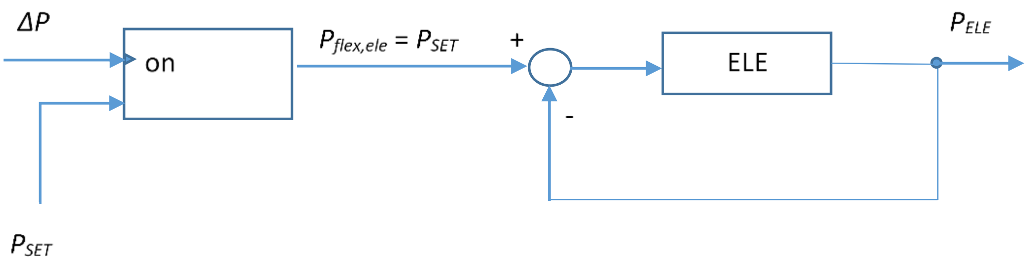


Figure 5-6: Control chain for case B.

When the mismatch is zero, the control system operates for bringing the electrolyser to its setpoint P_{SET}. This is functional for allowing the partial recovery of negative mismatch (explained in Case A).

Case C: $\Delta P \geq 0$ and $\Delta P \leq P_{SET}$

The control scheme handling the Case C is shown in Figure 5-7.

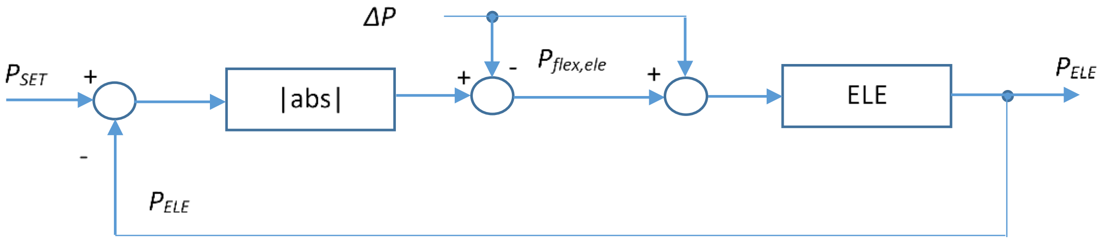


Figure 5-7: Control chain for case C.

In this case, the mismatch is positive, but is not big enough for supplying the electrolyser at the setpoint P_{SET}. For this reason, a further effort (represented by $P_{flex,ele}$) is necessary for permitting the electrolyser to reach the setpoint P_{SET}.

The block |abs| is necessary because even in case of $P_{SET} < P_{ele}$, the energy content corresponding to ΔP could be not sufficient due to the ramp down for moving from P_{ele} to P_{SET}.

Case D: $\Delta P \geq 0$ and $P_{SET} < \Delta P < P_{nom,ele}$

The control model in Case D is shown in Figure 5-8.

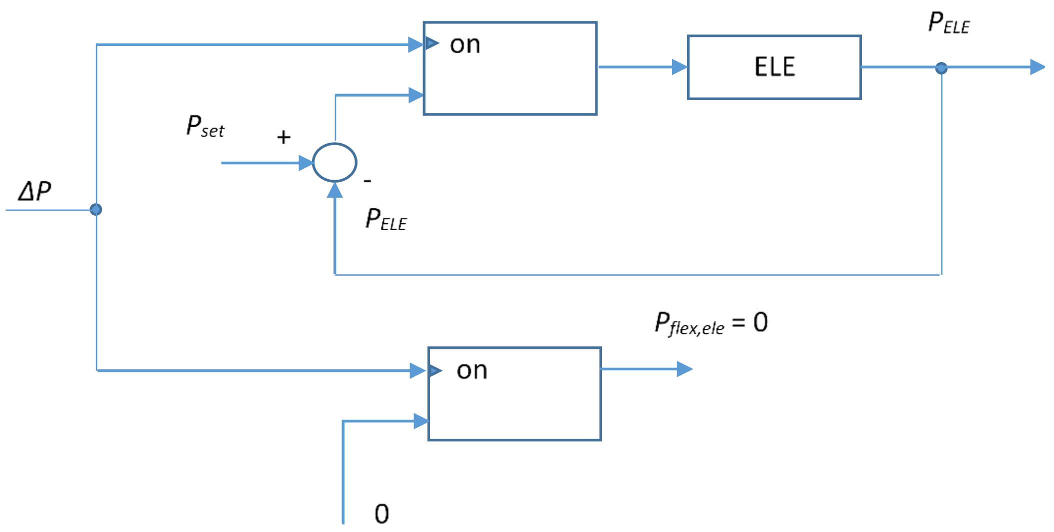


Figure 5-8: Control chain for case D.

In this case, the mismatch is higher than P_{set} and can supply the electrolyser by itself (i.e., $P_{flex.ele} = 0$).

Case E: $\Delta P \geq 0$ and $\Delta P \geq P_{nom,ele}$

The control model in Case E is shown in Figure 5-9.

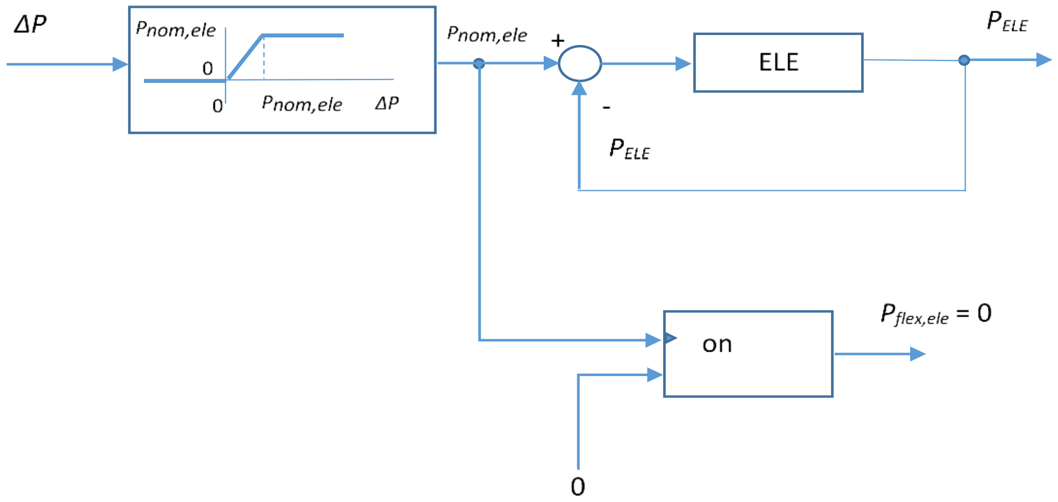


Figure 5-9: Control chain for case E.

In this case, the mismatch is higher than $P_{nom,ele}$ and, once it is saturated at $P_{nom,ele}$, it can supply the electrolyser by itself (i.e., $P_{flex.ele} = 0$).

Variants based on C1: the control schemes C2 and C3

By starting from the control scheme C1, two more schemes have been suggested:

- Control scheme C2: in this case, the control scheme, based on the cases above, adds an additional control limiting the recovery of the positive mismatch (this is for avoiding a decrease of the performance of the system in terms of total unbalancing).
- Control scheme C3: in this case the block FLEX_CCGT recovers the negative unbalances and can always provide to the grid up to P_{SET} (while in the control scheme C1 only a power up to $P_{flex,ele}$ can be provided to the grid).

Control scheme C4

The last control scheme differs from the three above, because at the beginning and at the end of every time step the electrolyser operates at its P_{SET}. Furthermore, it is supposed that the electrolyser is always supplied at P_{SET} thanks to the functional block FLEX_CCGT. Since this fact, the electrolyser can recover only positive unbalance of maximum magnitude $\Delta P_{MAX} = P_{nom} - P_{SET}$, and, in case of negative unbalance, the system can provide to the network a power covering at maximum an unbalance equal to $\Delta P_{min} = P_{SET} - P_{min}$.

The flow chart of the control scheme is shown in Figure 5-10. First of all, the control reads the following input data: the values of the nominal power of the electrolyser P_{nom}, the set value P_{SET}, the energy unbalance ΔE, the analysis time step Δt, the function linking the production of H_2 to the input electrical power feeding the electrolyser $H_2 = f(P_{ele})$, and the saturation values ΔP_{MAX} and ΔP_{min}.

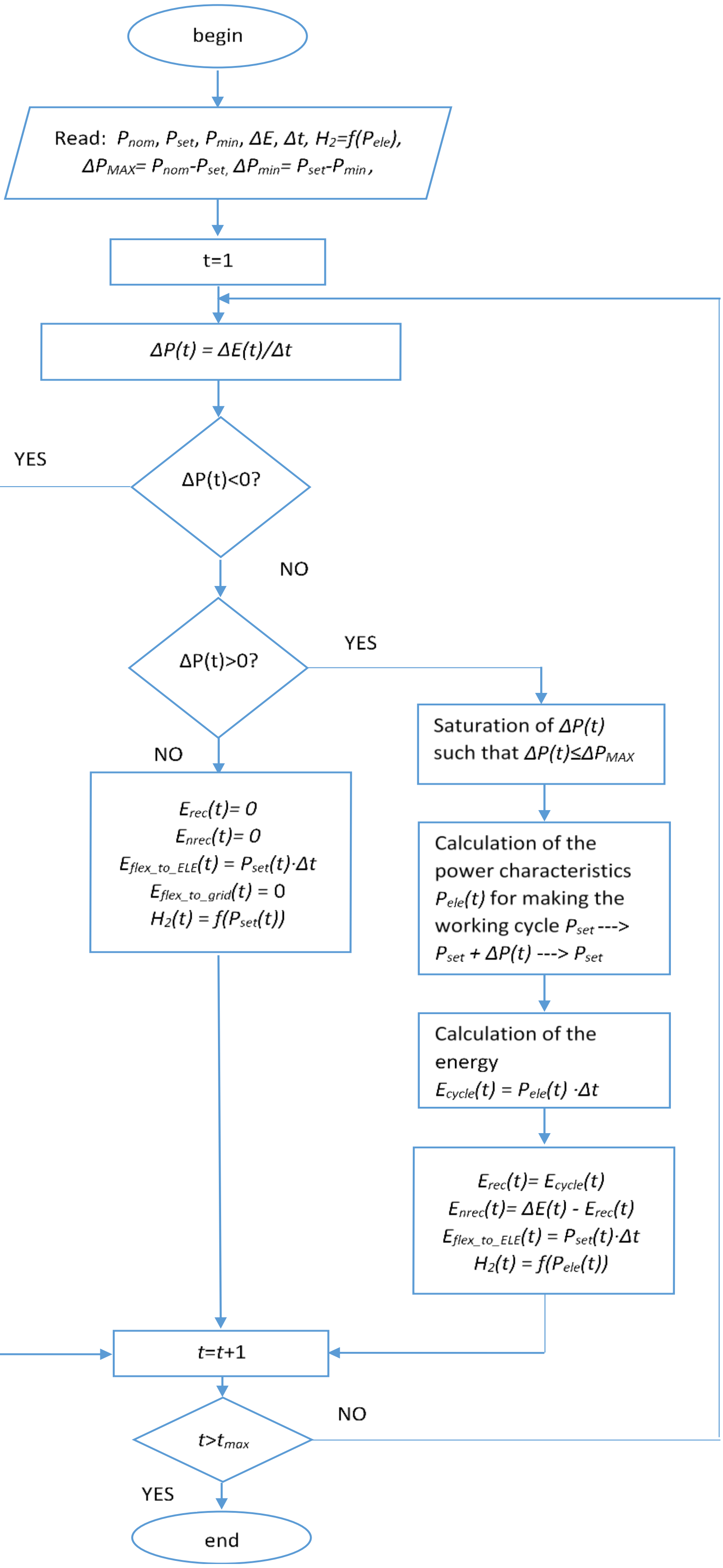


Figure 5-10: Flow chart control scheme C4.

According to the value of the unbalance ΔP, three different control actions are made.

Control C4: Case $\Delta P > 0$

In case of positive unbalance, the system can recover the difference between the nominal power P_{nom} and the set power P_{SET}. During the time step Δt, the electrolyser makes the work cycle $P_{SET} \rightarrow P_{SET} + \Delta P(t) \rightarrow P_{SET}$ [8].

The energy corresponding to that work cycle is the portion of the energy unbalance recovered by the electrolyser. Due to the knowledge of the characteristic $H_2(t)=f(P_{ele}(t))$, the production of hydrogen is calculated. Furthermore, the calculation of the energy not recovered, i.e. $E_{nrec}(t)$, and the energy $E_{flex_to_ELE}$I(t) provided to the electrolyser by the block FLEX_CCGT is made.

Control C4: Case $\Delta P = 0$

When there is no unbalance, the block FLEX_CCGT supplies the electrolyser at its P_{SET}. Also in this case, the production of hydrogen is not zero.

Control C4: Case $\Delta P < 0$

In case of negative unbalance, a portion of the power coming from the block FLEX_CCGT and supplying the electrolyser is used to reduce the negative unbalance. The electrolyser makes the work cycle $P_{SET} \rightarrow P_{min} \rightarrow P_{SET}$, allowing to provide to the grid an additional power called $P_{grid}(t)$ with work cycle $0 \rightarrow |\Delta P(t)| \rightarrow 0$. By making this, the negative unbalance can be reduced.

5.1.3 Simulations

Input for Simulations

As remarked at the beginning of section 5, the power plant under analysis has a nominal power of 400 MW and, during the year 2015, operated with the unbalances reported in Table 5-3. The unbalances have been reported both with time step width Δt = 1 min and Δt = 15 min. The latter one is the sum of 15 values of energy unbalance measured every minute.

Table 5-3: Unbalance of the gas-fired power plant

Power plant unbalance (Δt = 1 min)	Positive $\Delta E_{pos,1\ min}$	15673	[MWh]
	Negative $\Delta E_{neg,\ 1\ min}$	–24642	[MWh]
	Net unbalance (1 min)	–8969	[MWh]
Power plant unbalance (Δt = 15 min)	Positive $\Delta E_{pos,15\ min}$	6600	[MWh]
	Negative $\Delta E_{neg,\ 15\ min}$	–15569	[MWh]
	Net unbalance (15 min)	–8969	[MWh]

From the Table 5-3 it is evident that by considering both Δt = 1 min and Δt = 15 min the negative unbalance is higher than the positive unbalance. It is worth to note that the net unbalance is equal with the two time intervals, but the magnitude of the positive and negative unbalances is lower with a 15-minute time interval.

The size of the electrolyser has been chosen equal to P_{nom} = 5 MW (i.e., 1.25% of the power plant nominal power) and the values of P_{SET} have been chosen equal to [10% 25% 50% 100%] P_{nom}.

For the calculation of the production of SNG, the following assumptions have been made:

[8] It is worth to note that the expression $\Delta P(t)$ indicates the unbalance at the time instant t and this value is constant in the range $t \rightarrow t + \Delta t$

- H_2 density: 0.0899 kg/Nm^3
- Lower heating value H_2: 0.03 MWh/kg
- Efficiency of methanation module: 75%
- Efficiency of CCGT plant: 55%
- The efficiency of the electrolyser is obtained by applying the model reported in Section 5.1.1.

Simulation Output

First of all, an alkaline electrolyser has been considered in the simulation. The minimum power is thus set to 5% P_{nom}. The results are reported in Table 5-4.

Table 5-4: Results from using the alkaline electrolyser[8]

Control Type	P_{SET}	E_{rec_pos} [MWh] (%$\Delta E_{pos,1\,min}$)	E_{rec_neg} [MWh] (%$\Delta E_{neg,1\,min}$)	$E_{flex\_to\_ELE}$ [MWh]	$E_{flex\_to\_ELE}$ [MWh_{CH4}]	$E_{\_flex\_tot}$ [MWh]	$E_{\_flex\_tot}$ [MWh_{CH4}]	H_2 [m^3]	SNG [MWh]
Control C1	**10%**	7,868 (50.2%)	110 (0.4%)	**1,082**	3,774	2,185	3,973	1,823,068	**3,688**
	25%	7,886 (50.3%)	333 (1.4%)	**2,991**	7,250	4,320	7,855	2,169,604	**4,389**
	50%	7,925 (50.6%)	644 (2.6%)	6,777	14,138	8,420	15,310	2,856,395	5,778
	100%	7,985 (50.9%)	1,130 (4.6%)	15,617	30,218	17,750	32,273	4,454,409	9,010
Control C2	**10%**	5,012 (32.0%)	64 (0.3%)	**2,260**	4,108	2,323	4,225	1,343,553	**2,718**
	25%	5,058 (32.3%)	159 (0.6%)	3,656	6,648	3,815	6,937	1,602,189	3,241
	50%	5,122 (32.7%)	320 (1.3%)	6,413	11,660	6,734	12,243	2,108,719	4,265
	100%	5,226 (33.3%)	616 (2.5%)	12,954	23,554	13,570	24,673	3,301,371	6,678
Control C3	**10%**	7,868 (50.2%)	893 (3.6%)	**2,076**	3,774	2,969	5,397	1,823,068	**3,688**
	25%	7,886 (50.3%)	3,000 (12.2%)	**3,988**	7,250	6,989	12,707	2,169,604	**4,389**
	50%	7,925 (50.6%)	5,589 (22.7%)	7,776	14,138	13,365	24,299	2,856,395	5,778
	100%	7,985 (50.9%)	9,258 (37.6%)	16,620	30,218	25,878	47,050	4,454,409	9,010
Control C4	**10%**	5,727 (36.5%)	925 (3.8%)	**3,354**	6,098	4,279	7780	1,689,692	**4,557**
	25%	5,366 (34.2%)	2,886 (11.7%)	7011	12,747	9,898	17996	2,295,247	6,190
	50%	4,411 (28.1%)	4,916 (20.0%)	13,467	24,485	18,384	33425	3,299,373	8,898
	100%	0 (0 %)	6,924 (28.1%)	27,248	49,542	34,172	62131	5,005,258	13,499

After that, a PEM electrolyser has been considered in the simulation. The minimum power is thus set to 0 (Table 5-5)

Table 5-5: Results from using the PEM electrolyser[9]

Control Type	P_{SET}	E_{rec_pos} [MWh] (%$\Delta E_{pos,1\,min}$)	E_{rec_neg} [MWh] (%$\Delta E_{neg,1\,min}$)	$E_{flex\_to\_ELE}$ [MWh]	$E_{flex\_to\_ELE}$ [MWh_{CH4}]	$E_{\_flex\_tot}$ [MWh]	$E_{\_flex\_tot}$ [MWh_{CH4}]	H_2 [m^3]	SNG [MWh]
Control C1	**10%**	7,851 (50.1%)	195 (0.8%)	**1,082**	**1,967**	1,277	2,322	1,624,336	**3,286**
	25%	7,872 (50.2%)	416 (1.7%)	**2,991**	5,438	3,407	6,195	1,971,006	**3,987**
	50%	7,913 (50.5%)	705 (2.9%)	6,777	12,322	7,482	13,604	2,658,083	5,377
	100%	7,977 (50.9%)	1,176 (4.8%)	15,617	28,395	16,793	30,533	4,256,768	8,610
Control C2	**10%**	5,012 (31.9%)	103 (0.4%)	**877**	**1,595**	980	1,782	1,071,176	**2,167**
	25%	5,057 (32.2%)	202 (0.8%)	**2,297**	4176	2,499	4,544	1,334,696	**2,700**
	50%	5,120 (32.7%)	356 (1.4%)	5,073	9224	5,429	9,871	1,884,200	3,811
	100%	5,224 (33.3%)	647 (2.6%)	1,164	2116	1,811	3,293	3,043,033	6,155
Control C3	**10%**	7,851 (50.1%)	1,673 (6.8%)	**1,082**	**1,967**	2,755	5,009	1,624,336	**3,286**
	25%	7,872 (50.2%)	3,573 (14.5%)	**2,991**	5,438	6,564	11,935	1,971,006	**3,987**
	50%	7,913 (50.5%)	6,028 (24.5%)	6,777	12,322	12,805	23,282	2,658,083	5,377
	100%	7,977 (50.9%)	9,534 (38.7%)	15,617	28,395	25,151	45,729	4,256,768	8,610
Control C4	**10%**	5,727 (36.5%)	1,691 (6.9%)	**2,418**	4,396	4,109	7,470	1,498,727	**3,032**
	25%	5,366 (34.2%)	3,376 (13.7%)	6,203	11,278	9,579	17,415.	2,114,316	4,277
	50%	4,411 (28.1%)	5,221 (21.2%)	12,814	23,298	18,035	32,790	3,130,782	6,333
	100%	0 (0 %)	7,021 (28.5%)	26,797	48,721	33,818	61,487	4,850,919	9,812

[9]Legend: Blue: it indicates the cases in which the output of SNG [MWh] is higher than the additional electricity $E_{flex\_to\_ELE}$ [MWh] provided by the flexibility block
Bold blue: it highlights the output of SNG [MWh], the additional electricity $E_{flex\_to\_ELE}$ [MWh] provided by the flexibility block in the blue cases, as well as the $E_{flex\_to\_ELE}$ [MWh of CH_4] when it is lower than the output energy (i.e., SNG [MWh])
Red: it highlights in the blue cases the additional electricity $E_{flex\_to\_ELE}$ expressed in [MWh of CH_4] (i.e., the primary energy used to produce it) when it is higher than the output (i.e., SNG [MWh of CH_4])

5.1.4 Results

- General considerations

In general, the three first control schemes permit a recovery of a large share of positive unbalance (from 31% to 50%), while the recovery of the negative unbalance is not efficient (from 0.4% to 38%).

It is worth to note that with a relatively small size of the electrolyser (i.e., 1.5% of the power plant nominal power), it is possible to recover a wide percentage of the total positive unbalance.

The control schemes C1 and C3 have the same performance in the recovery of the positive unbalance, because the control strategy implemented is exactly the same. Conversely, the negative unbalance is recovered more when the control C3 is applied, because the block FLEX_CCGT operates for recovering the negative unbalance with amplitude up to P_{nom}, while the control scheme C1 tries to use only the power of the block FLEX_CCGT available in the previous time step.

The control scheme C2 limits its control action according to the energy recovered every 15 minutes. If the sum of the energy not recovered from the beginning of each 15-minute interval to the present time step becomes negative (i.e., it has been recovered too much positive unbalance), the control action is stopped. Due to this, the percentage of recovery is lower both for positive and negative unbalances. Furthermore, in this case the consumption of fuel is lower than the previous control.

Completely different is the control C4: in this case the range of recovered positive and negative is limited from P_{SET} to P_{nom} (positive unbalance) and from 0 to P_{SET} (negative unbalance). So, the percentage of recovery of the positive unbalance is lower than the previous controls, becoming zero when P_{SET} is equal to P_{nom}. In case of negative unbalance, this control does not work as good as the control C3, but it is better than the control C1 and C2.

- Differences between the two electrolysers

The use of the alkaline electrolyser with the first three control schemes allows a slightly better recovery of the positive unbalance. This comes from the fact that the electrolyser has to work at P_{min}, and the time necessary to arrive at the final state of the electrolyser is lower. Thanks to this, the electrolyser works longer at the maximum allowed power for the existing unbalance, recovering a slightly higher share of positive unbalance than using the PEM electrolyser. However, this fact is paid in terms of energy that has to be provided to the electrolyser for guaranteeing the correct operation.

Conversely, the control C4 guarantees the same recovery of positive unbalance both with alkaline and PEM electrolyser, because in both cases the unbalance that can be recovered is limited at $\Delta P_{MAX} = P_{nom} - P_{SET}$. In case of negative unbalance, the alkaline electrolyser presents lower performance due to the P_{min} that has to be guaranteed (i.e., the maximum negative unbalance that can be recovered is $\Delta P_{min} = P_{SET} - P_{min.}$

- Convenience in terms of energy point of view

From the energy point of view, it is worth to see that in case of using an alkaline electrolyser, all the control schemes have at least one configuration (marked in blue in Table 5-4 and Table 5-5) with a gas production (MWh CH_4) higher than the additional electricity $E_{flex\_to\_ELE}$

necessary for the operation of the electrolyser. However, if the electricity used has to be produced by the CCGT, the consumption of gas is higher than the amount produced from the methanation (marked in red), and so no control scheme reaches the energy breakeven.

When the PEM electrolyser is used, the first three control schemes allow producing more gas than necessary to produce the additional electricity to feed the electrolyser, when P_{SET} is 10%.

The control C4, conversely, requests more gas than the amount of energy that can be produced with all the values of P_{SET}.

5.1.5 Cost/benefit analysis (CBA)

Applying the four control schemes to the CCGT is supposed to reduce the penalties paid by the owner of the power plant to the TSO due to unbalances, with real data coming from the Italian situation.

The CBA has been made by using as indicator the EBITDA[10] (Earnings Before Interest, Taxes, Depreciation and Amortization), which compares the situation before installation of the electrolyser and the situation after installation of the electrolysers. The EBITDA is negative if the installation does not provide benefits.

The variation of the EBITDA (i.e., ΔEBITDA) for the PEM electrolyser applied to the unbalancing related to the year 2015 is shown in Figure 5-11.

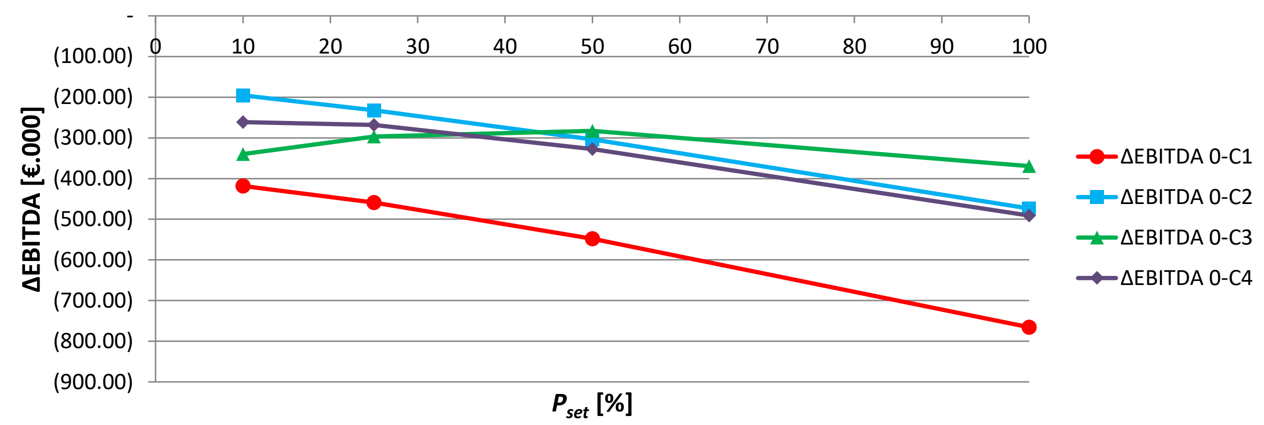


Figure 5-11: Earnings Before Interest, Taxes, Depreciation and Amortization for the PEM electrolyser

The figure shows that the "best" control scheme changes according to the value of P_{SET}. In particular, the control scheme C2 permits better performances up to $P_{SET} \approx 0.45\ P_{nom}$, while with higher P_{SET} the control scheme C3 results more performance. The control C4 has an intermediate behaviour until $P_{SET} \approx 0.35\ P_{nom}$, and then results the worst in terms of EBITDA.

As seen, this particular application cannot improve the performance of the power plant. This fact is due to different causes:

1) The positive unbalance is often monetised from the TSO, depending on the condition of the zone where the power plant is located. This fact means that the use of the electrolyser can provide a worse condition in terms of global balance, exactly because the electrolyser is able

[10] EBITDA reports a company's profits before interest on debt and taxes owed or paid to the government are subtracted (http://financial-dictionary.thefreedictionary.com/EBITDA).

to recover very large share of positive unbalance, without an equivalent recover of negative unbalance.

2) The condition of the zone (i.e., if it is characterised by a positive or negative global unbalance) is not known *a priori*. For this reason, the creation of a control scheme allowing the improvement of the performance of the plant by reducing the penalties results difficult (not all the inputs are known).

3) The unbalance measured from the TSO is the total unbalance every 15 minutes. This fact leads to having sort of a "mean value", taking into account both the negative and positive unbalance. The performances in terms of residual unbalance of the four control schemes are reported in Table 5-6. By considering the sum over 15-minute ranges, the situation is different from before. As highlighted previously, the control schemes are based on the time step Δt = 1 min, and thus the controls drive the electrolyser on the basis of the unbalance existing in that time interval, providing the performances reported in Table 5-4 and Table 5-5. However, by summing up the results over 15-minute ranges the situation changes: for instance, the control C2 presents all the residual unbalance higher than the initial one, because the electrolyser recovered "too much" positive unbalance, by transforming some 15-minute intervals which were globally positively unbalanced in the interval characterised by negative unbalance. Another meaningful example is provided by the control C4, which, with P_{SET} = 100%, does not recover any positive unbalance (i.e., the residual positive unbalance is more than 100%), and the recovery of the negative unbalance permits to transform some initially positively unbalanced intervals into intervals characterised by zero unbalance or slight negative unbalance.

Table 5-6: Control results with a time step of 15 minutes

P_{SET}	Control C1		Control C2		Control C3		Control C4	
	$\Delta E_{pos,15\ min}$	$\Delta E_{neg,\ 15\ min}$	$\Delta E_{pos,15\ min}$	$\Delta E_{neg,\ 15\ min}$	$\Delta E_{pos,15\ min}$	$\Delta E_{neg,\ 15\ min}$	$\Delta E_{pos,15\ min}$	$\Delta E_{neg,\ 15\ min}$
10%	2,574.02 (39.0%)	19,197.54 (123.3%)	2,933 (44.4%)	16,808 (108.0%)	2,672 (40.5%)	17,818 (114.4%)	3,678 (55.7%)	16,682 (107.1%)
25%	2,582.36 (39.1%)	19,006.72 (122.1%)	2,938 (44.5%)	16,761 (107.7%)	2,855 (43.2%)	16,122 (103.5%)	4,151 (62.9%)	15,108 (97.0%)
50%	2,593.65 (39.3%)	18,769.60 (120.6%)	2,946 (44.6%)	16,677 (107.1%)	3,145 (47.6%)	13,998 (89.9%)	5,145 (77.9%)	13,302 (85.4%)
100%	2,620.51 (39.7%)	18,390.20 (118.1%)	2,962 (44.9%)	16,507 (106%)	3,740 (56.7%)	11,151 (71.6%)	9,114 (138.1%)	11,061 (71.0%)

5.2 Supporting a CCGT for offering capacity downward

5.2.1 Coupling PtG with a CCGT for offering capacity downward

The analysis considers the possible use of PtG for supporting a CCGT to offer the regulation of capacity downward (i.e., the reduction of generation) on the Balancing Market (BM). Without the use of PtG, the power plant has to reduce its production by varying the amount of gas feeding the plant, whereas with PtG the power plant can be operated at constant power. The latter case produces a "virtual" reduction of the power seen by the network. The two options are represented in Figure 5-12 and Figure 5-13, respectively.

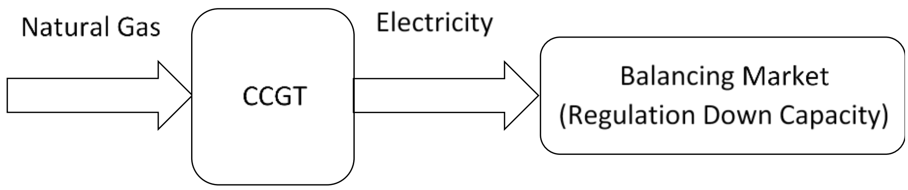


Figure 5-12: Scheme of the base case example with dispatchable power plant

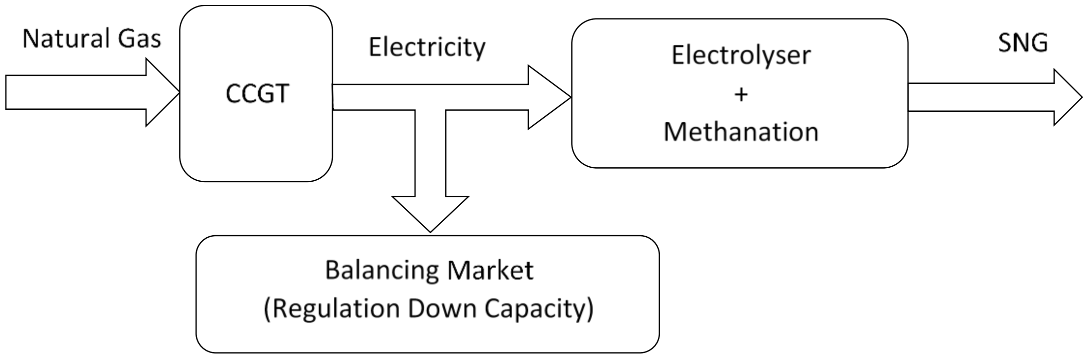


Figure 5-13: Scheme of the base case example with dispatchable power plant

The assumptions made for the study considering only the CCGT plant (i.e., Figure 5-12are the following ones:

1. The owner of the CCGT plant schedules one month of scheduled maintenance, during August (the power plant thus is not available).
2. The power plant is able to sell the additional power on the Day Ahead Market (DAM) for 98% of the time in which it is available.
3. The possibility to participate in the BM varies from 25% to 100%.
4. The price recognized in the BM is higher than in DAM, i.e., $p_{BM} = 1.75 \cdot p_{DAM}$.
5. The strategy of use is based on the identification of a certain number of hours of the day in which the plant offers its service of downward capacity (variable from 1 to 7).

The further parameters used in the simulation are reported in Table 5-7.

Table 5-7: Inputs and parameters considered in the example

Variable	Unit	Value
P_{el}	[MW]	2.5
η_{CCGT}	–	0.55
η_{PtG}	–	0.45
c_{CCGT}	[€/MWh]	35.0
p_{NG}	[€/MWh]	20.0

The results reporting the ΔEBITDA between operating a CCGT with and without PtG are shown in Figure 5-14. The curves show that the option PtG is not convenient from the economic point of view, because the cost (in terms of additional fuel burnt by the CCGT plant for supplying the electrolyser) is not recovered by selling the produced SNG. If the probability to participate in the market increases, the ΔEBITDA becomes less negative, even if it is still more convenient to operate on the control of the gas turbine instead of installing PtG.

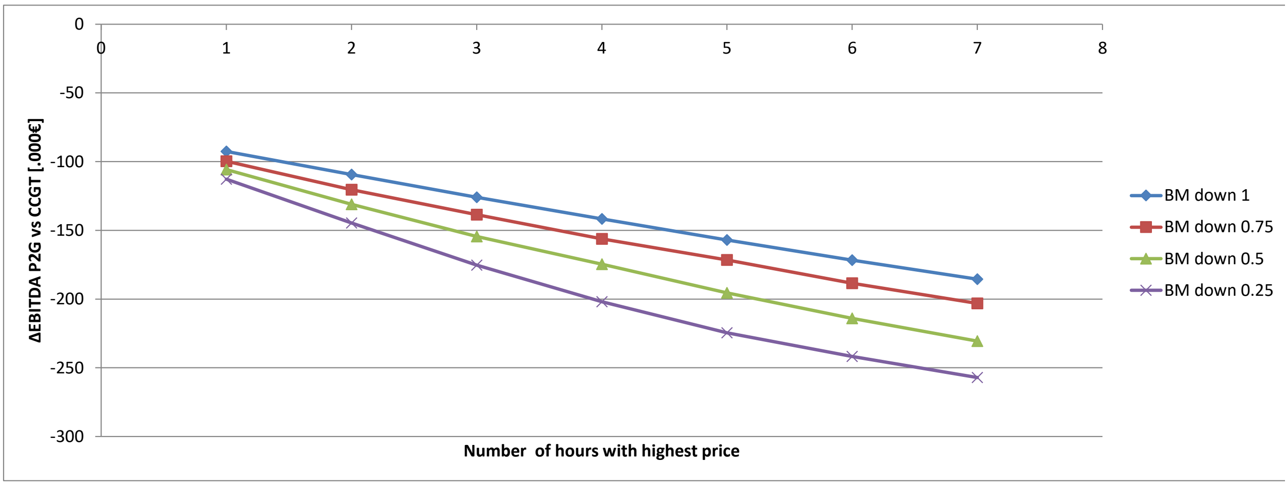


Figure 5-14: ΔEBITDA between the use of CCGT, and CCGT coupled with PtG for offering downward capacity on the BM

5.2.2 Coupling batteries with a CCGT for offering capacity downward

For understanding the behaviour of alternative storage technologies, the use of batteries has been simulated. In order to compare batteries with the PtG system, only the downward capacity market has been considered. It has been assumed that the probability to enter in the market is 50%. The participation is divided between the participation in the downward capacity market and in the upward capacity market. Figure 5-15, Figure 5-16, and Figure 5-17 show the results for the case in which batteries participate only in the downward capacity market (label 100%) to the case in which they participate in the downward capacity market only 25% of the time (that means they participate for 75% of the time in the upward capacity market).

Three technologies have been considered as meaningful:

1. Lithium batteries (Li-Ion) technology
2. Vanadium redox flow batteries (VRBF)
3. Sodium sulphur (NaS) batteries.

The Li-Ion batteries are a common electrochemical storage, widely developed during the last 30 years also for bulk systems. They are characterised by a relatively high efficiency, i.e., 0.85–0.90. The efficiency indicated is the round-trip efficiency, which does not consider the auxiliary services. Because Lithium batteries do not need any particular high energy-consuming auxiliary, it is valid to consider an efficiency about 80% due to the losses of the connection (inverter + transformer).

VRFB are still under development for grid applications. The global efficiency can be estimated at around 70% [93].

The NaS batteries: this kind of batteries is one of the most proven one for grid applications. This is the technology used by the Italian TSO (i.e., Terna SpA) for handling network congestion in central Italy. The overall efficiency is at 60–70% (the value has been estimated by starting from [94]).

The hypothesis used in this kind of analysis are reported in Table 5-8.

Table 5-8: Data considered for the comparison with batteries

Variable	Unit	Value
P_{el}	[MW]	2.5
Capacity	[MWh]	25
$\eta_{Li\text{-}Ion}$	–	0.80
η_{VRBF}	–	0.70
η_{NaS}	–	0.65
$CAPEX_{SNG}$	[€/kW]	750
$OPEX_{SNG}$	[€/kW]	24.75
$CAPEX_{Li\text{-}Ion}$	[€/kW]	463
$CAPEX_{Li\text{-}Ion}$	[€/kWh]	795
$OPEX_{Li\text{-}Ion}$	[€/kW/y]	6.9
$CAPEX_{VRBF}$	[€/kW]	490
$CAPEX_{VRBF}$	[€/kWh]	467
$OPEX_{VRBF}$	[€/kW/y]	8.5
$CAPEX_{NaS}$	[€/kW]	366
$CAPEX_{NaS}$	[€/kWh]	298
$OPEX_{NaS}$	[€/kW/y]	3.6
c_{CCGT}	[€/MWh]	35.0
p_{NG}	[€/MWh]	20.0

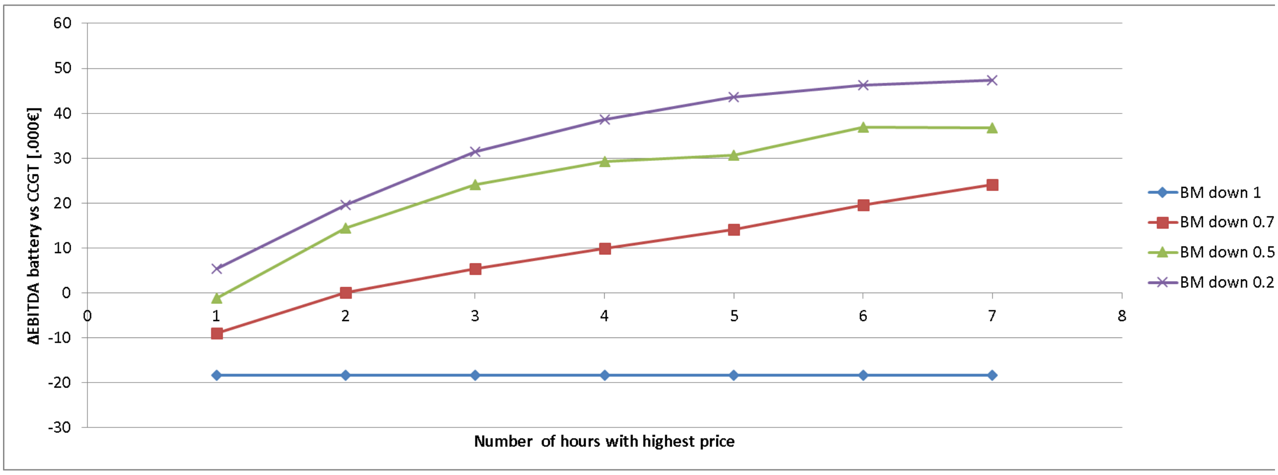


Figure 5-15: ΔEBITDA between the use of CCGT, and CCGT coupled with a Li-Ion battery for offering downward capacity in the BM

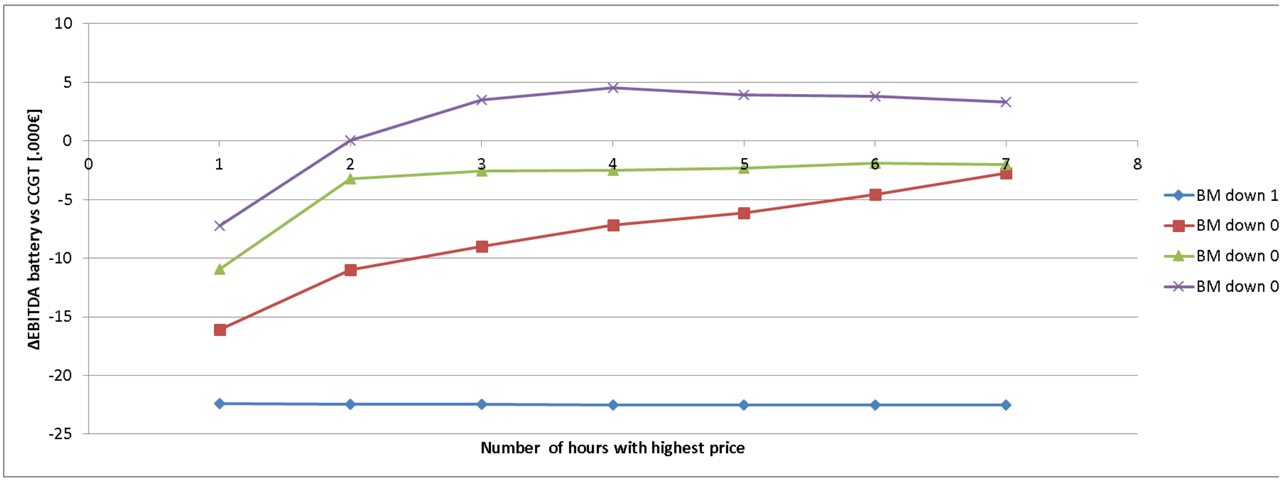


Figure 5-16: ΔEBITDA between the use of CCGT, and CCGT coupled with a VRBF battery for offering downward capacity in the BM

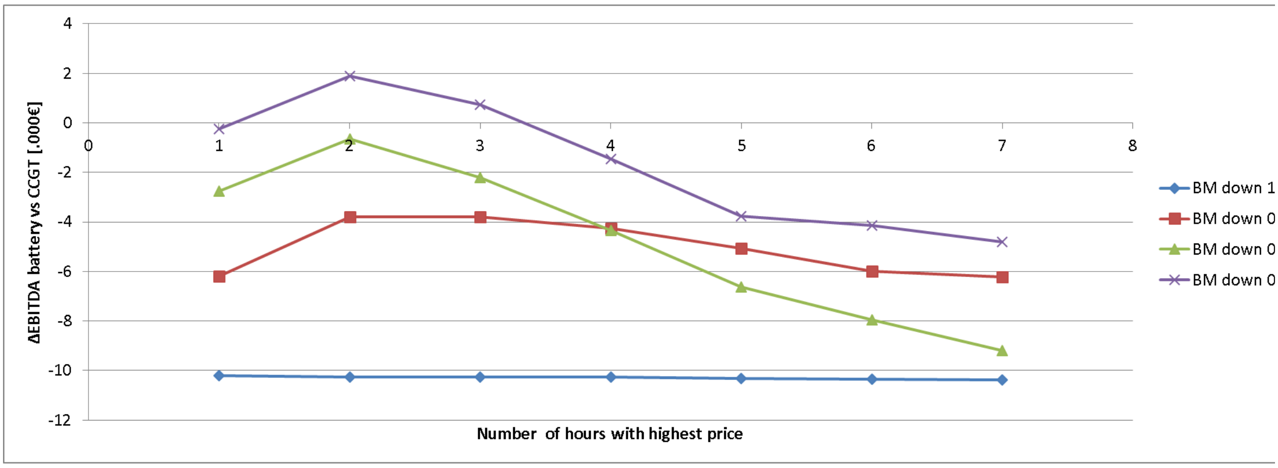


Figure 5-17: ΔEBITDA between the use of CCGT, and CCGT coupled with a NaS battery for offering downward capacity in the BM

As it is possible to note, if the batteries are used only in the downward capacity market, the ΔEBITDA is always negative. This fact indicates that, independently of the technology implemented, the offer of the downward capacity in the market is not convenient anyway.

The use of the Li-Ion battery is the most convenient, both in terms of ΔEBITDA, and in terms of different market conditions that allow getting a positive ΔEBITDA.

NaS batteries, which have an efficiency closer to the PtG one, show a similar behaviour to PtG (i.e., the more hours the plant is operated, the more negative is the ΔEBITDA).

The use of VRBF results conveniently only when they participate in the downward capacity market for 25% of the time, while in the other conditions the EBITDA is negative.

It is worth to note that the simulations with PtG and batteries have been conducted at the same condition. The comparison among Figure 5-14 and the three figures referred to the batteries (i.e., Figure 5-15, Figure 5-16, and Figure 5-17) highlights that the non-participation to the upward capacity market penalises the PtG with respect to the other technologies.

6 PtG with non-dispatchable power plants

As remarked in Section 2.1.1, the generation park is based both by dispatchable and non-dispatchable generators. This section aims to investigate the application of PtG coupled with non-dispatchable generation by presenting the point of view of the owner of the power plant. In particular, this section aims to draw the following points:

- Providing an introductive analysis regarding the cost of electricity in five different electricity European market, for understanding the level of incentive which has to be guaranteed to SNG for providing reasonable pay-back time (Section 6.1).

- Providing a perspective application aiming to allow the participation of RES-based power plants to the balancing market (thanks to the combined use of PtG and clusters of microturbines), when network constraints do not allow the complete dispatch of the energy produced, and the consequent loss of incomes due to the impossibility to participate at the day-ahead market (Section 6.2)

6.1 Analysis of the incentives for PtG with RES

The first example considers the cost of electricity in 2015 on different electricity European markets, i.e.:

- Nord Pool[11]

- Italy

- Austria/Germany

- France

- Switzerland

The idea is to evaluate the incentive necessary for making PtG feasible. Table 6-1 shows the hypothesis of the study.

Starting from the selling price of Natural Gas (NG), comprehensive of the incentive recognized, it is possible to establish a threshold indicating when it is convenient, for a non-dispatchable power plant, to feed the PtG system and produce SNG rather than selling electricity directly.

If $P_{el} < \frac{C_{NG}+incentive}{\eta_{\mathrm{PtG}}}$, it is profitable to produce SNG, while if $P_{el} > \frac{C_{NG}+incentive}{\eta_{\mathrm{PtG}}}$, it is more profitable to sell electricity directly into the grid.

Table 6-1: Parameters considered in the study

Variable	Unit	Value
Cost$_{NG}$	[€/MWh]	15-20-25-30-35
CAPEX	[k€/MW]	750
OPEX	[k€/MW]	24.75

[11] The Nord Pool is actually divided in different markets. Here, this market is described by using the system price (http://www.nordpoolspot.com/How-does-it-work/Bidding-areas/). The system price is calculated based on the sale and purchase orders disregarding the available transmission capacity between the bidding areas in the Nordic market. The system price is the Nordic reference price for trading and clearing of most financial contracts.

Incentives	[€/MWh]	0-10-20-40-60-80-100

The screenshot of the calculation sheet is reported in Figure 6-1.

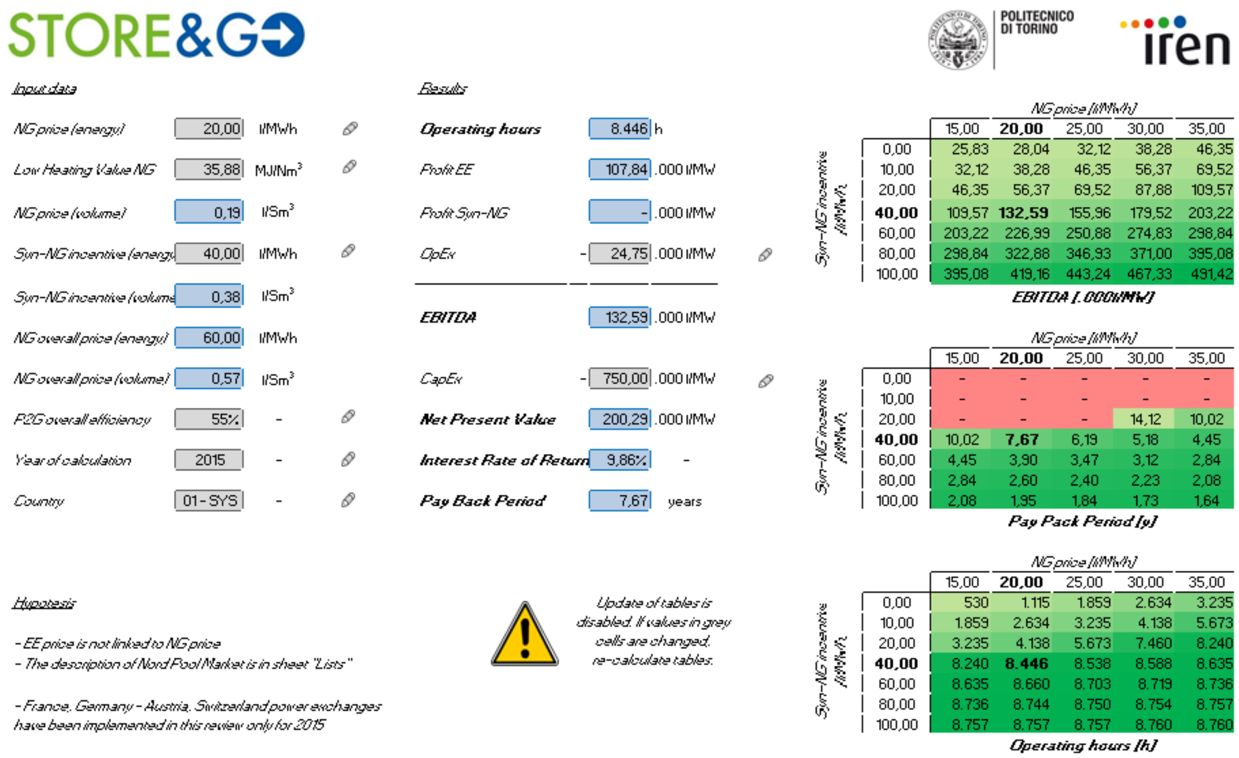


Figure 6-1: Screenshot of the calculation sheet developed

6.1.1 Nord Pool

The EBITDA regarding the analysis related to Nord Pool are shown in Figure 6-2 (in case of different incentives), whereas the operating hours, function of the different incentives, are reported in Figure 6-3. Both variables increase when the incentive and the NG price increase.

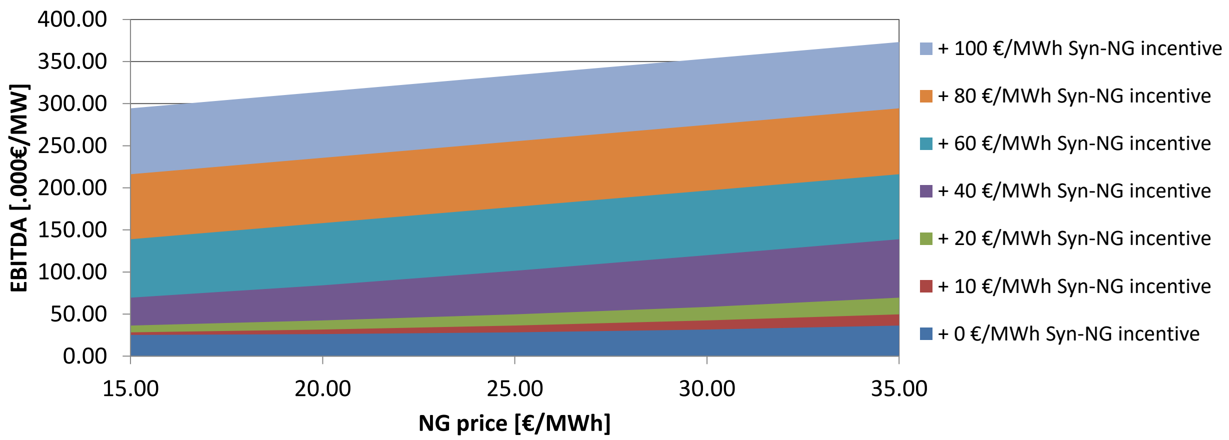


Figure 6-2: EBITDA with different value of incentives and with different gas prices

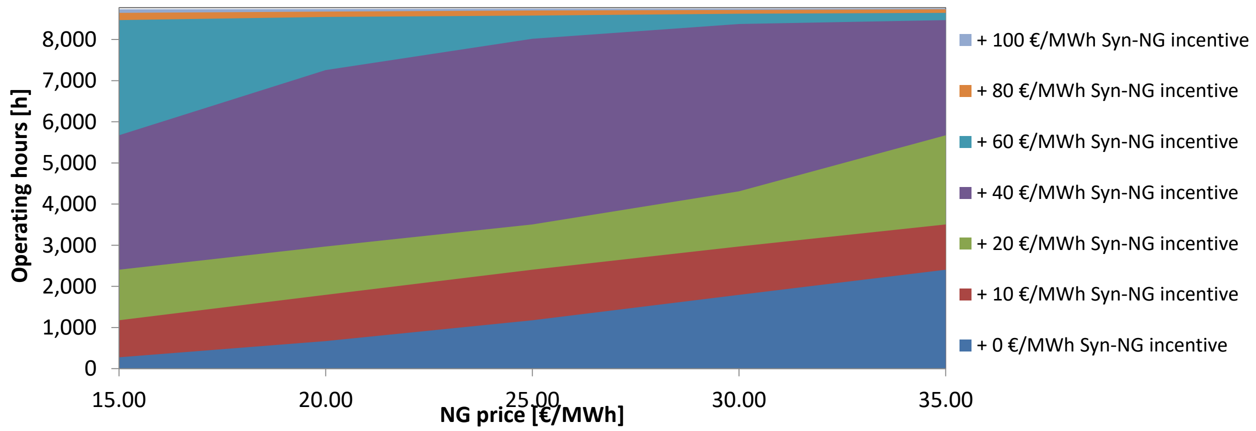


Figure 6-3: Operating hours with different value of incentives and with different gas prices

It is worth to note that an incentive of 60 €/MWh on the natural gas price allows a Pay Back Period of about 6 years (as shown in Figure 6-4)

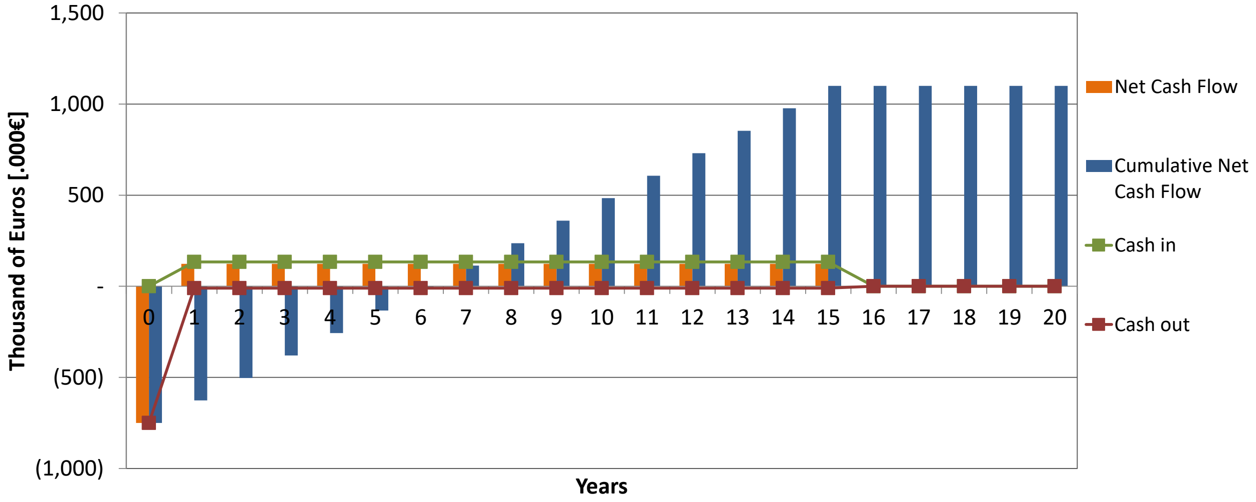


Figure 6-4: Operating hours with different values of incentives and with different gas prices

6.1.2 Italy

The EBITDA regarding the analysis related to Italy are shown in Figure 6-5 (in case of different incentives), whereas the operating hours, function of the different incentives, are reported in Figure 6-6. Both variables increase when the incentive and the NG price increase.

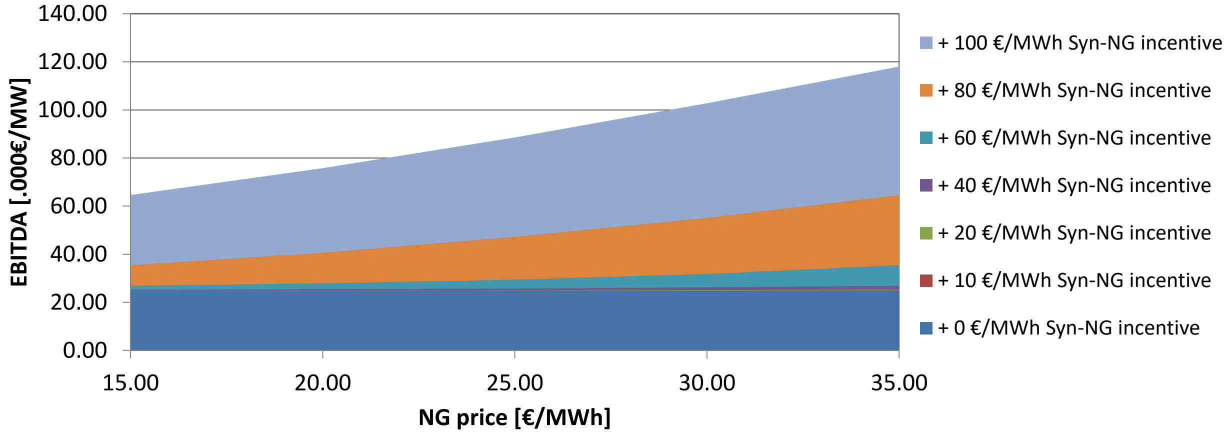


Figure 6-5: EBITDA with different values of incentives and with different gas prices

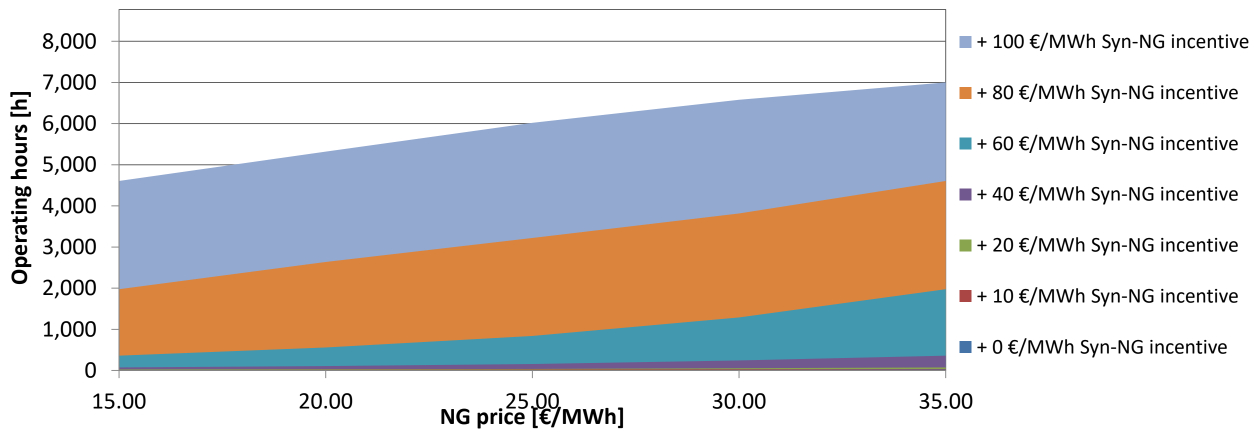


Figure 6-6: Operating hours with different values of incentives and with different gas prices

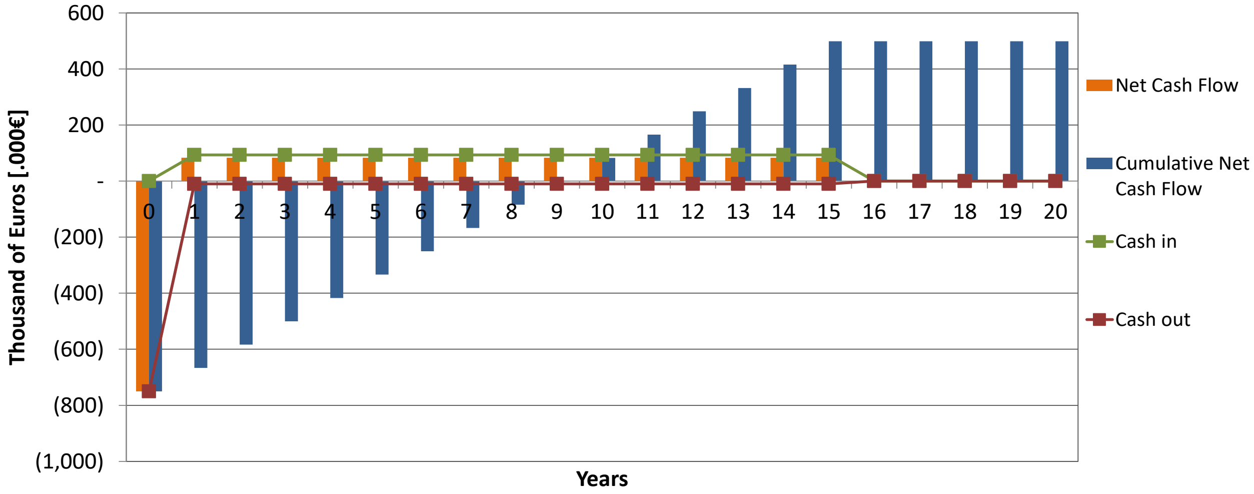


Figure 6-7 : Cumulative Net Cash Flow with an incentive of 100 €/MWh and NG price of 35€/MWh

In the Italian market, it is necessary to add an incentive of 100 €/MWh to the natural gas price, in order to have an acceptable Pay Back Time (9 years), but considering a price of NG about 35 €/MWh (as shown in Figure 6-7).

6.1.3 Austria/Germany

The EBITDA regarding the analysis related to the Austria/Germany are shown in Figure 6-8 (in case of different incentives), whereas the operating hours, function of the different incentives, are reported in Figure 6-9. Both variables increase when the incentive and the NG price increase.

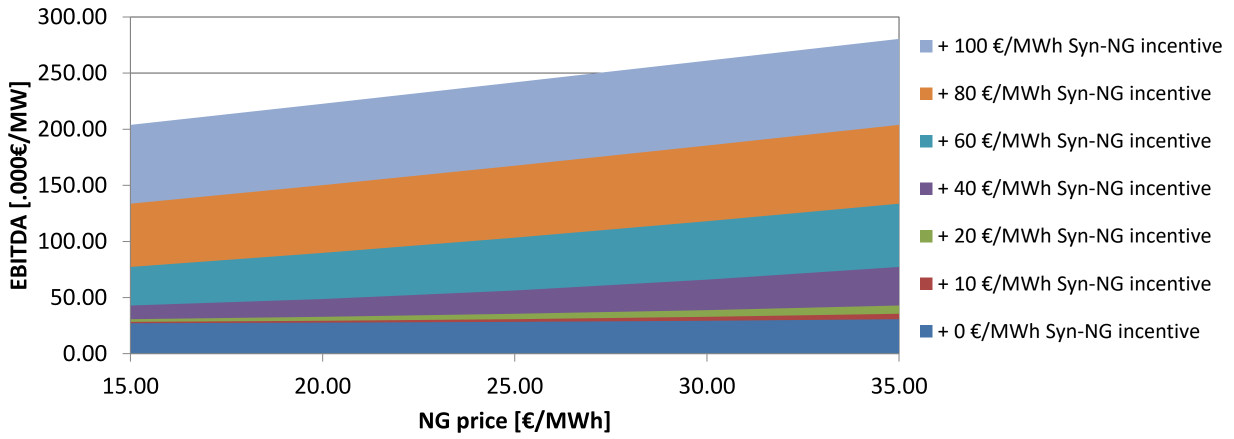


Figure 6-8: EBITDA with different values of incentives and with different gas prices

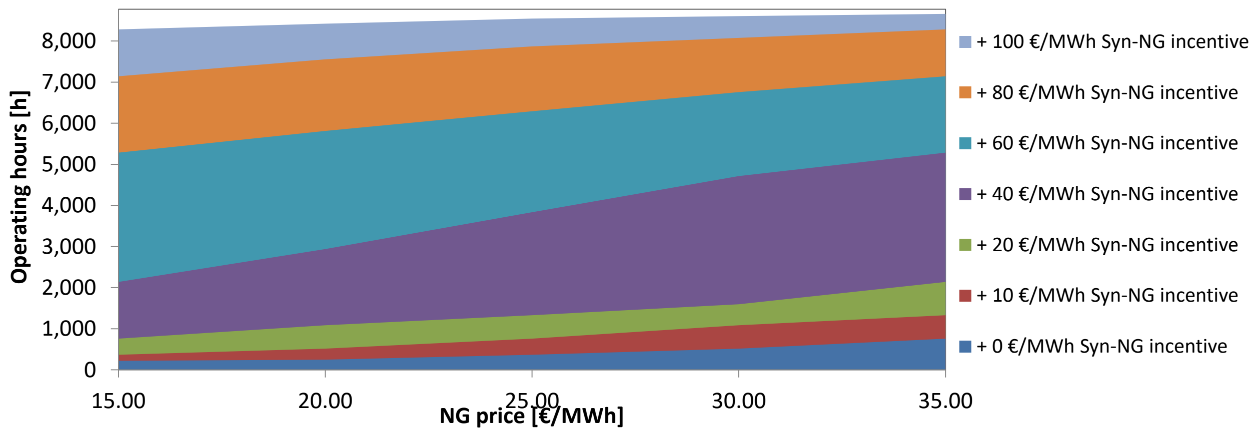


Figure 6-9: Operating hours with different values of incentives and with different gas prices

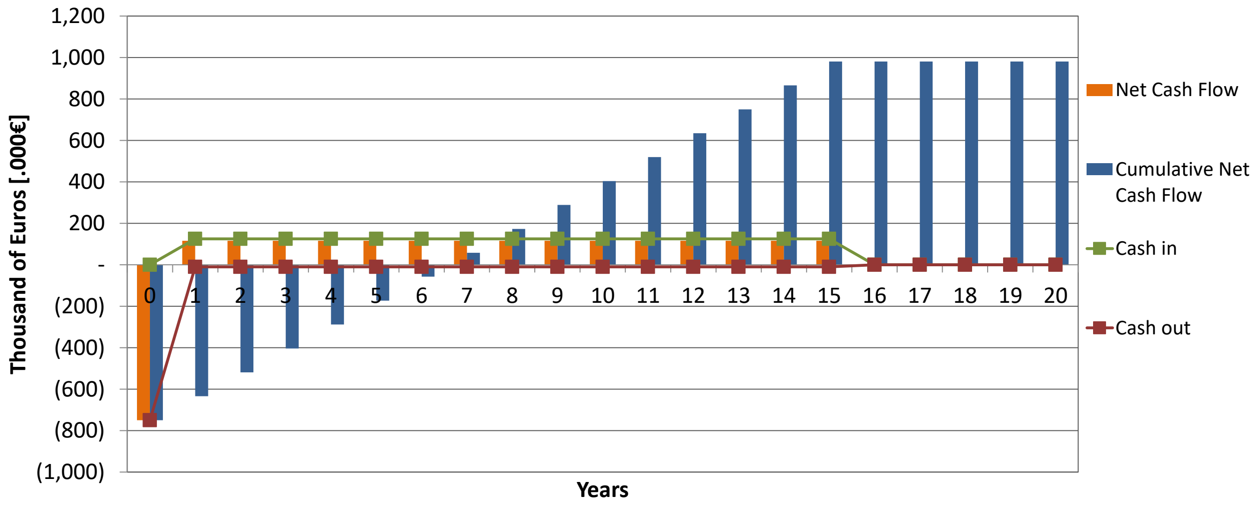


Figure 6-10 : Cumulative Net Cash Flow with an incentive of 80 €/MWh

In the Austrian-German market, it is enough to add an incentive of 80 €/MWh to the natural gas price, in order to have an acceptable Pay Back Time (7 years), as shown in Figure 6-10.

6.1.4 France

The EBITDA regarding the analysis related to France are shown in Figure 6-11 (in case of different incentives), whereas the operating hours, function of the different incentives, are reported in Figure 6-12. Both variables increase when the incentive and the NG price increase.

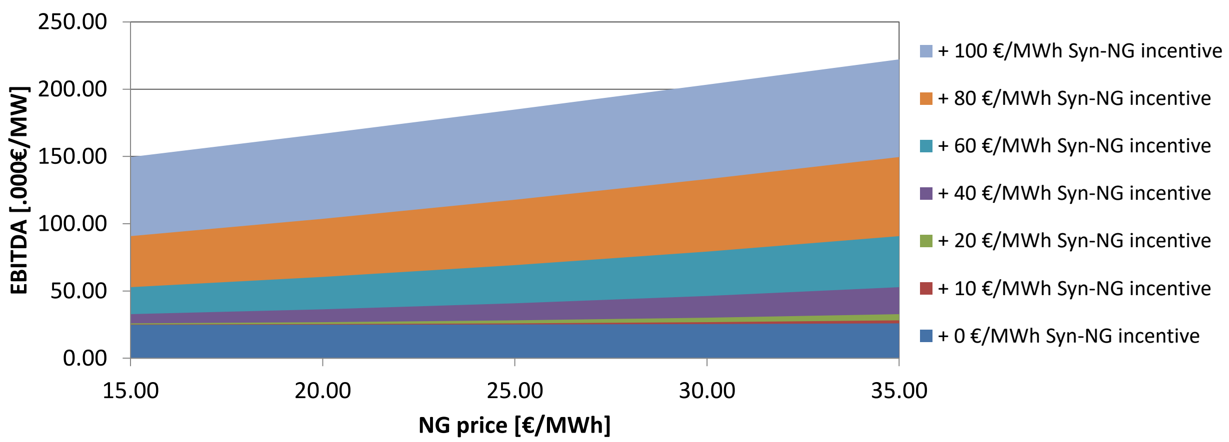


Figure 6-11: EBITDA with different values of incentives and with different gas prices

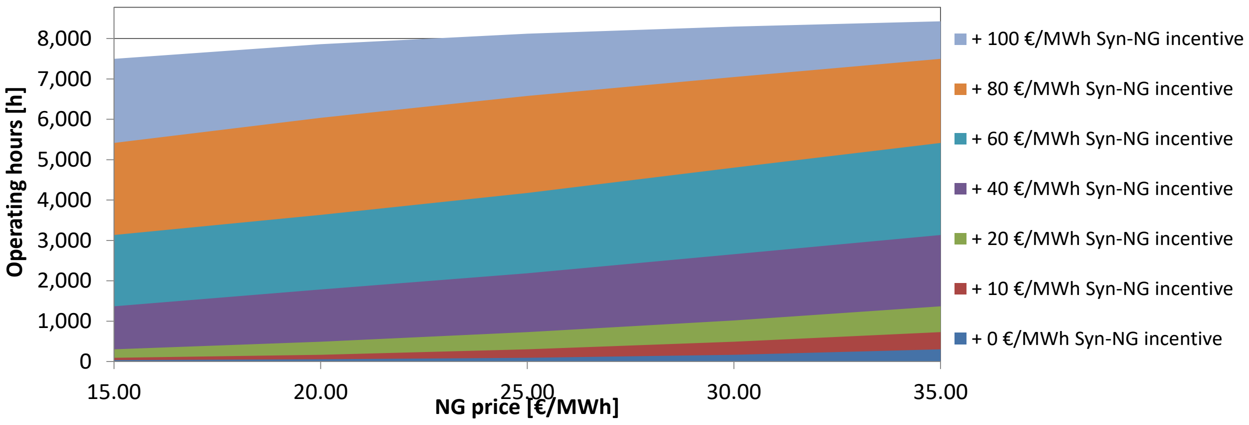


Figure 6-12: Operating hours with different values of incentives and with different gas prices

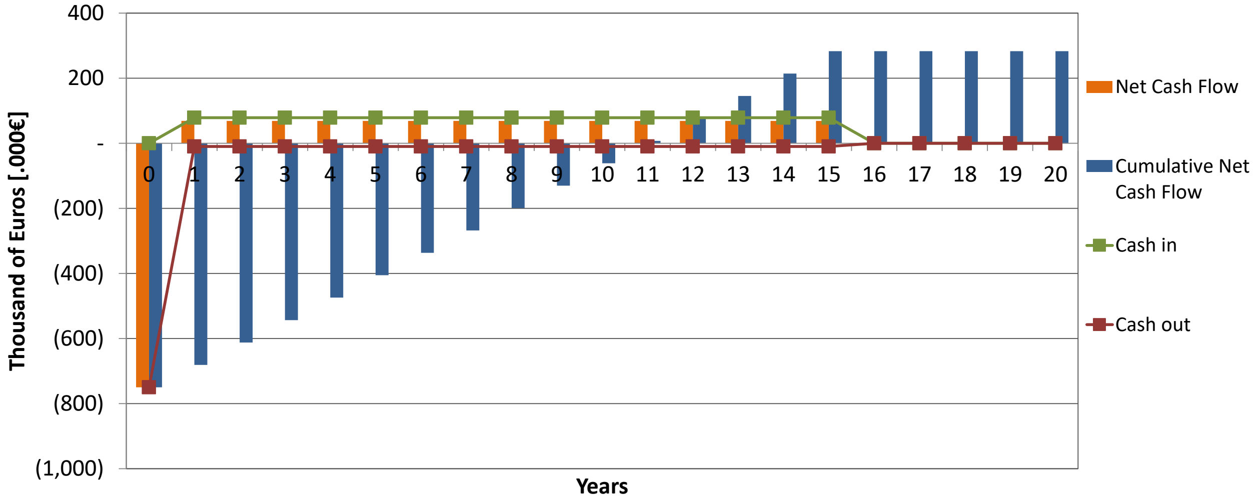


Figure 6-13 : Cumulative Net Cash Flow with an incentive of 80 €/MWh

In the French market, it is necessary to add an incentive of 80 €/MWh to the natural gas price, to have an acceptable Pay Back Time (11 years), as shown in Figure 6-13.

6.1.5 Switzerland

The EBITDA regarding the analysis related to Switzerland are shown in Figure 6-14:

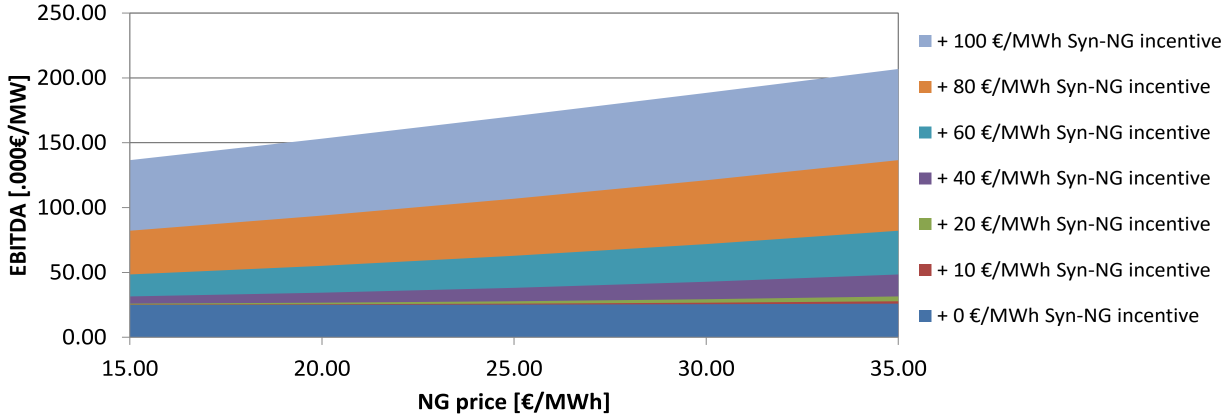


Figure 6-14: EBITDA with different values of incentives and with different gas prices

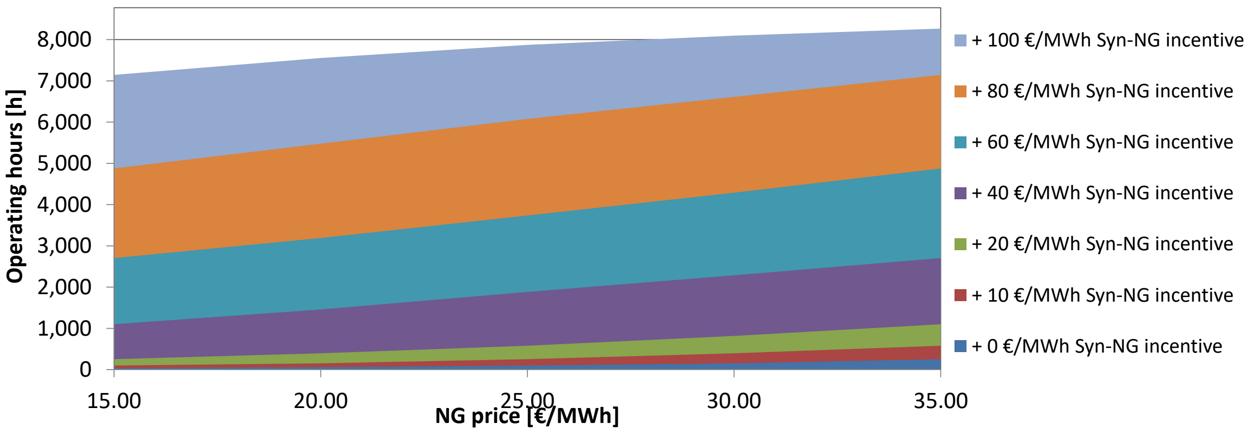


Figure 6-15: Operating hours with different values of incentives and with different gas prices

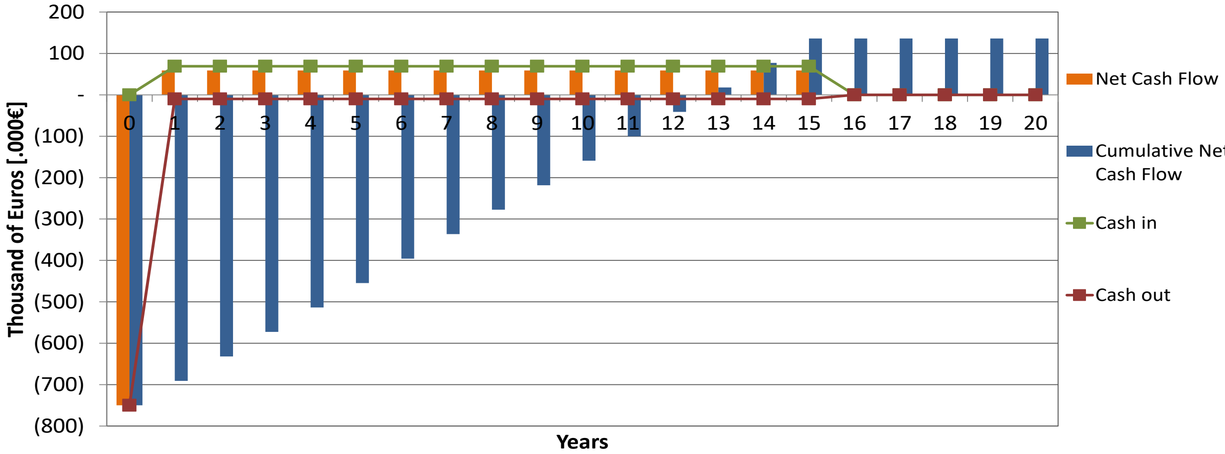


Figure 6-16: Cumulative Net Cash Flow with an incentive of 80 €/MWh

In the Swiss market, it is necessary to add an incentive of 80 €/MWh to the natural gas price, in order to have an acceptable Pay Back Time (13 years).

6.2 New business for non-dispatchable power plants

The data used as electricity prices refer to the year 2015 and represent the electricity prices p_{DAM} received from the DAM in Italy. The assumptions made for the study are reported in the following sections.

In this case, the generator is a Virtual Power Plant (VPP) composed of different RES-based plant connected to the same portion of network.

Due to network issues, the grid operator limits the amount of power produced by the VPP that can be dispatched.

The base case (shown in Figure 6-17) implies the selling of the electricity at the DAM. The VPP can sell the energy produced for all hours in which the VPP is available (in fact, the energy produced by RES is always dispatched, unless network congestion).

The alternative case sees the coupling of a PtG plant and a cluster of gas-fired microturbines (Figure 6-18). In this case, the goal of the plant is to participate in both markets (i.e., DAM and BM), by producing gas which is stored (for example, by using the gas network) and burnt later into the cluster for participating to the BM.

The assumptions for the studies are as follows:

1) The owner of the VPP schedules 15 days of scheduled maintenance, during the second half of August (the VPP thus is not available).

2) The VPP coupled with PtG can sell on BM only for a limited number of hours, which are the hours in which it wins the competition on the market (fixed as matter of example to ρ_{BM}=60%)

3) The electricity price on the balancing market is equal to $(1+\Delta p)\cdot p_{DAM}$, where Δp represents an additional bonus (the examples will use Δp=0 and Δp=0.25).

4) The cluster of microturbines can operate only if the gas produced so far is sufficient to supply it. This fact means that the aim is to challenge the plant to be self-sufficient, i.e., it can use only the amount of gas that has been produced by it.

5) The minimum value of the cluster used is 0.5 MW. The other sizes are supposed to be composed of equal modules of the minimum size.

6) Furthermore, a minimum power has been imposed allowing the operation of the microturbine, i.e., P_{min} = 20% (referred to the minimum size of the modules composing the cluster)

7) The wind park is composed of 24 turbines of 2 MW each.

8) The maximum value of power that can be injected is 30 MW.

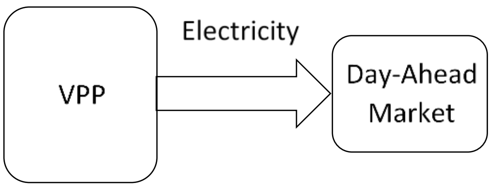


Figure 6-17 : Scheme of the base case example with RES-based VPP

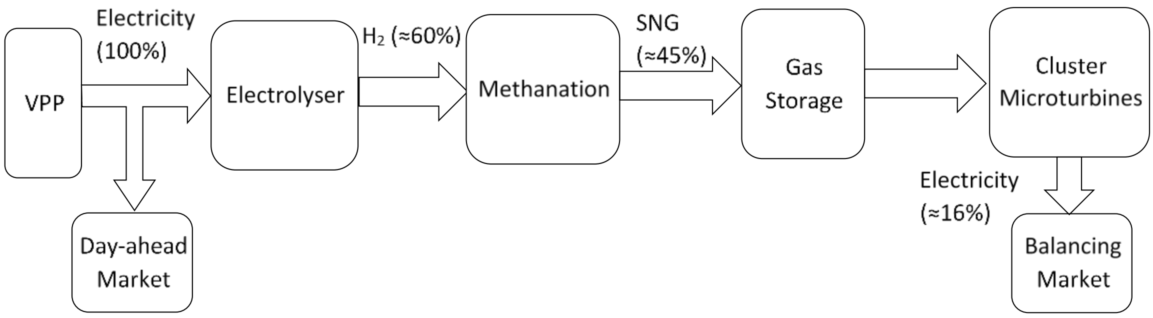


Figure 6-18: Scheme of the base case example with RES-based VPP

The cost function for the base case is essentially composed of the benefit coming from the selling of energy on the DAM. By indicating with $\boldsymbol{t}_{DAM}$ the vector with dimension N_{DAM} containing the time steps in which the VPP sells in the DAM, the benefit from selling is:

$$B_{baseCase} = \sum_{j=1}^{N_{DAM}} P_{DAM}(\boldsymbol{t}_{DAM}(j)) \cdot p_{DAM}(\boldsymbol{t}_{DAM}(j))$$

The cost function for the alternative case is composed of the benefit coming from the selling of energy in the DAM, the benefit coming from the selling of energy in the BM and the benefit coming from selling the excess of SNG as it is, i.e.:

$$B_{alternativeCase} = \sum_{j=1}^{N_{DAM}} P_{DAM}(\boldsymbol{t}_{DAM}(j)) \cdot p_{DAM}(\boldsymbol{t}_{DAM}(j)) + \sum_{k=1}^{N_{BM}} P_{el}(\boldsymbol{t}_{BM}(k)) \cdot \eta_{P2G} \cdot \eta_{uT} \cdot p_{BM}(\boldsymbol{t}_{BM}(k)) + \sum_{i=1}^{N_{SNG}} P_{el}(\boldsymbol{t}_{SNG}(i)) \cdot \eta_{P2G} \cdot p_{NG}(\boldsymbol{t}_{SNG}(i))$$

where $\boldsymbol{t}_{BM}$ is the vector containing the N_{BM} hours in which VPP works in BM, η_{uT} is the efficiency of the cluster of microturbines, and $\boldsymbol{t}_{SNG}$is the vector containing the N_{SNG}hours in which the plant sells the excess of gas to the gas network.

The additional cash flow due to the installation of the exploitation of PtG and microturbines is:

$$\begin{aligned}\Delta B_{alternativeCase} &= B_{alternativeCase} - B_{baseCase} \\ &= \sum_{k=1}^{N_{BM}} P_{el}(\boldsymbol{t}_{BM}(k)) \cdot \eta_{P2G} \cdot \eta_{uT} \cdot p_{BM}(\boldsymbol{t}_{BM}(k)) + \sum_{i=1}^{N_{SNG}} P_{el}(\boldsymbol{t}_{SNG}(i)) \cdot \eta_{P2G} \cdot p_{NG}(\boldsymbol{t}_{SNG}(i))\end{aligned}$$

The parameter used in the studies are reported in

Table 6-2.

Table 6-2: Data of the non-dispatchable plant example

Variable	Unit	Values
Size PtG	[MW]	0.5 – 1 – 1.5 – 2.5 – 5 – 10
Size cluster of turbines	[MW]	0.1–1, with step 0.1
P_{min} cluster	%	20%[12]
H_{uT}	-	0.35
η_{PtG}	-	0.45
p_{NG}	[€/MWh]	20.0
CAPEX cluster[13]	[M€/MW]	1.75
OPEX cluster[7]	[€/MWh]	15
Lifetime	[years]	20

The excess of RES during the year is shown in Figure 6-19, whereas the additional cash flows, composed by the terms due to the selling of the electricity in the BM, and the selling of gas is reported

[12] Referred to the minimum size of the cluster (i.e., 0.1 MW)
[13] Refrerence: https://www.energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/Forskning/Technology_data_for_energy_plants.pdf

in Figure 6-20 and Figure 6-21. The sum of the two terms (i.e., $\Delta B_{\mathrm{alternativeCase}}$) is shown in Figure 6-22.

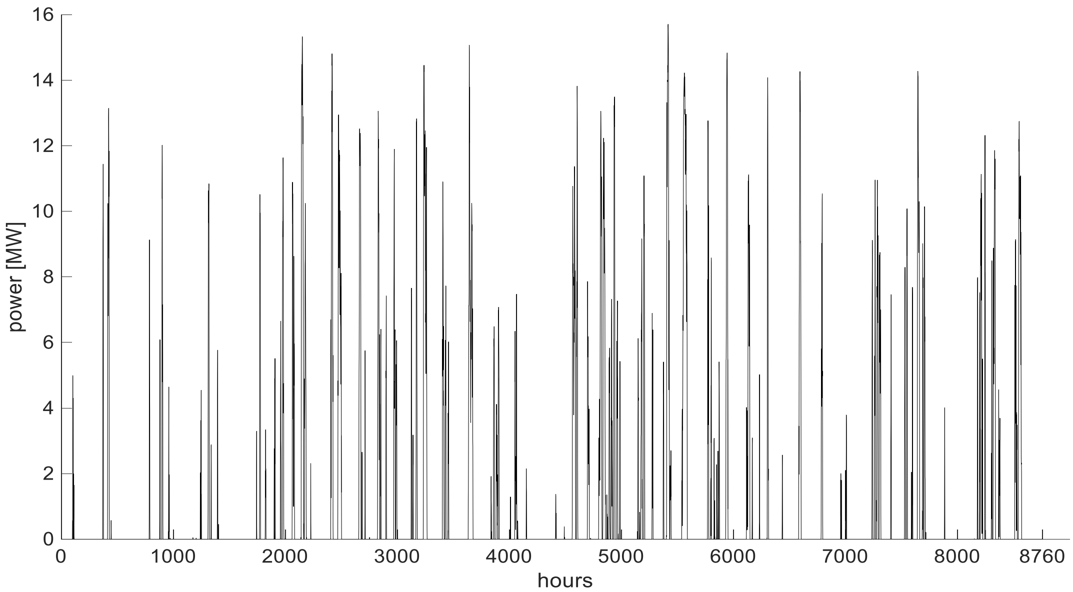


Figure 6-19 : Excess of RES in the case study

Figure 6-20 shows that the cash flow due to the selling of the electricity in the BM is depending on the size of the cluster used. Furthermore, the bigger the size of PtG, the higher the income from selling electricity, due to the higher amount of gas produced and hence usable in the microturbines.

The incomes from the selling of gas (Figure 6-21) are higher with small size cluster, because small clusters cannot burn completely the gas produced. This effect is higher with larger PtG facility.

The total income (Figure 6-22) is not really depending on the size of the cluster of microturbines, because the selling of gas and electricity can affect each other. It is worth to note that in case of PtG facilities with large size, the use of a small cluster of microturbines can result in any case conveniently, due to the selling of gas to the gas grid.

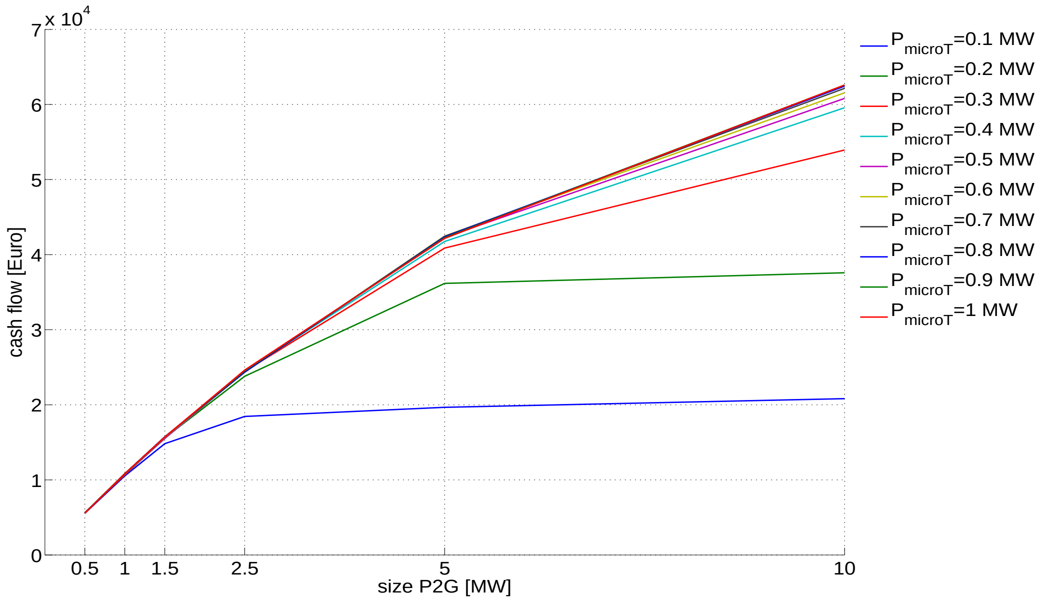


Figure 6-20 : Cash flow due to the sell of electricity in the BM (with $p_{BM} = p_{DAM}$)

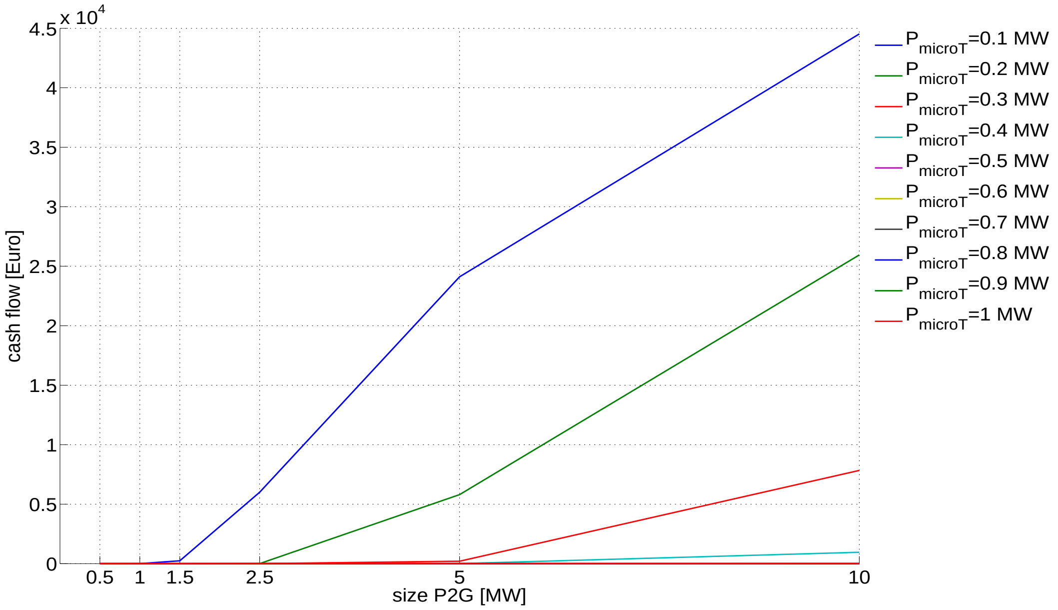


Figure 6-21: Cash flow due to the sell of gas in the BM (with $p_{BM} = p_{DAM}$)

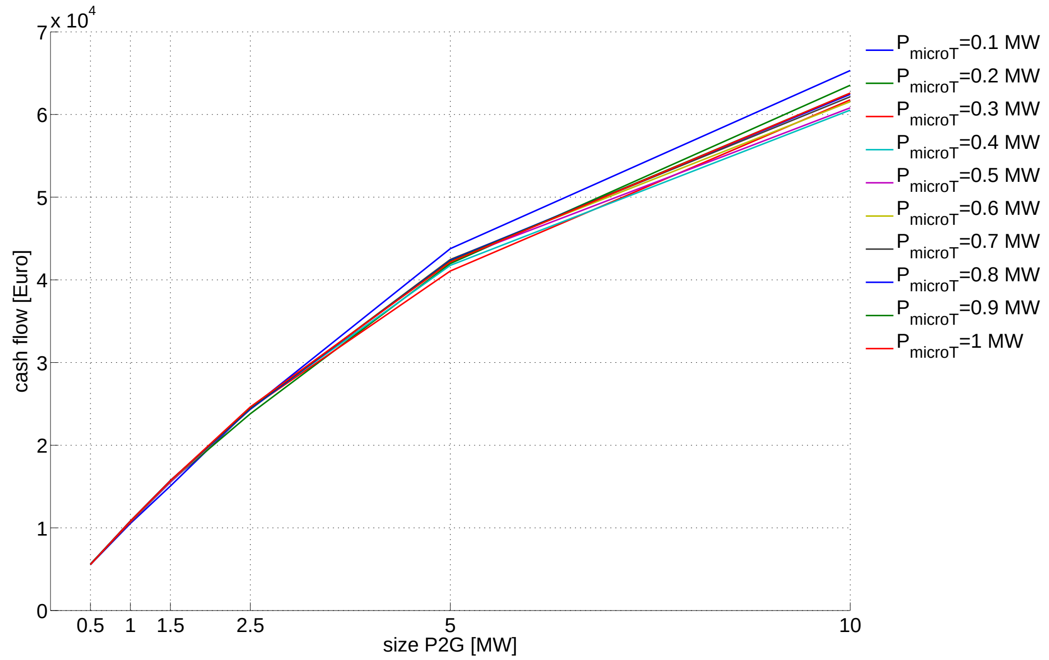


Figure 6-22: Additional cash flow due to both selling of electricity in the BM and selling of gas (with$p_{BM} = p_{DAM}$)

For the case with Δp=0.25, the results show in Figure 6-23 that the curves are exactly the same with respect to the ones in Figure 6-22, but the cash flow is higher (due to the higher price of the electricity in the BM).

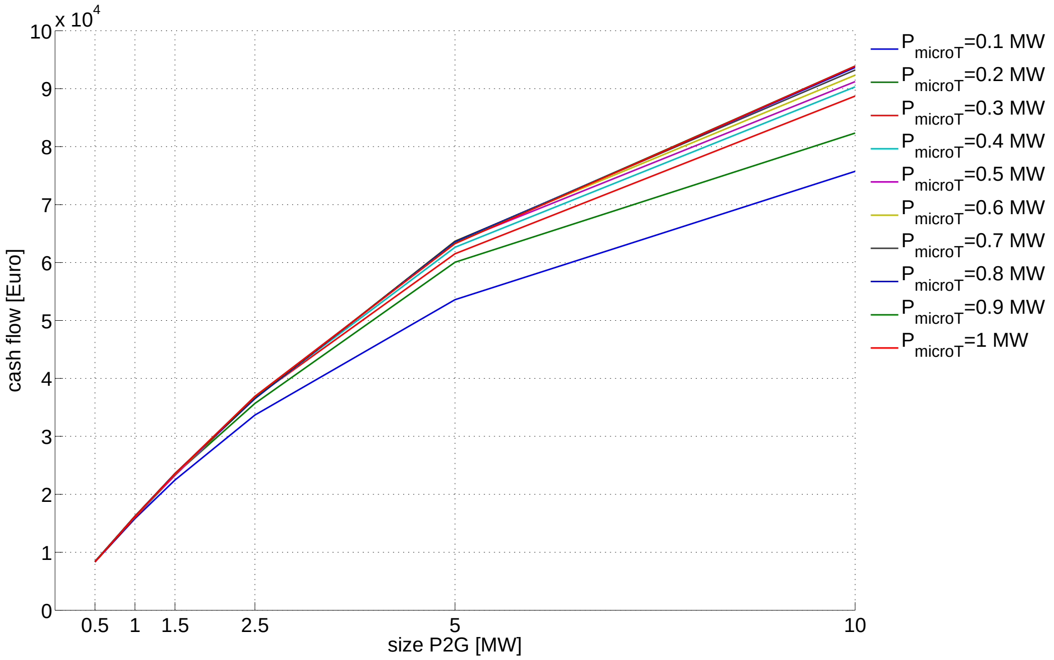


Figure 6-23 : Additional cash flow due to both selling of electricity in the BM and selling of gas (with $p_{BM} = 1.25 \cdot p_{DAM}$)

By starting from the cash flows shown above, the Net Present Value (NPV) and cumulative cash flow have been evaluated for the cases with $\rho_{BM} = 0.6$ and $\rho_{BM} = 1$.

The minimum value of Δp leading to positive NPV and the sizes of PtG and microturbines are reported in Table 6-3.

Table 6-3:Summary of the cases presenting positive NPV (limit 30 MW)

Probability BM	Size PtG [MW]	Size microturbines [MW]	Δp
$\rho_{BM} = 0.6$	1	0.1	8
	1.5	0.1	
$\rho_{BM} = 1$	1.5	0.1	7.5

As it is possible to see, the prices leading to a positive NPV, in this specific case study, are pretty high. This fact depends on that the excess of energy transformed in electricity and sold in the BM is limited during the year (it is about 8% of the total energy sold in the DAM).

The cash flow for the case with $\rho_{BM} = 1$ is shown in Figure 6-24: the pay-back time is about 12 years.

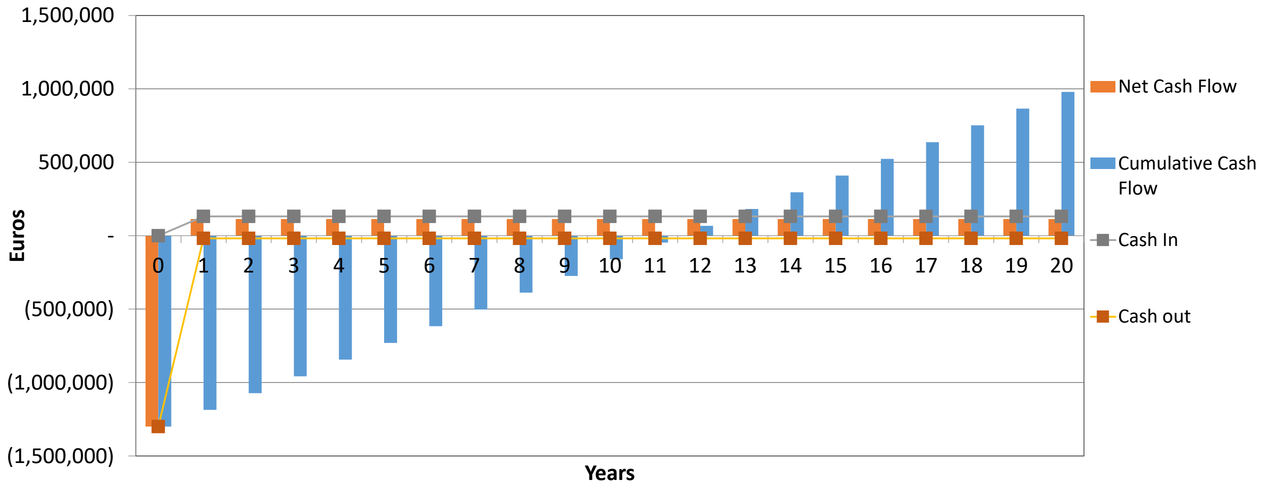


Figure 6-24: Business plan for the application under analysis with ρ_{BM} = 1 and Δp=7.5.

If the maximum power which can be injected into the network passes from 30 MW to 10 MW, then the combinations (shown in
Table 6-4) leading to a positive NPV are more than the ones obtained with maximum power 30 MW, and the price of the electricity should be 4 times the price of the DAM (i.e., Δp = 3).
It is worth to note that since the excess of RES is high, the most convenient investment would be the coupling of small PtG facilities with small clusters (production of methane limited and production of electricity made by using small electrical components), or big PtG facilities (that means large SNG production) coupled with electrical facilities, which can properly exploit it (relatively large size).

The cash flows for three cases (i.e., small plant P_{PtG} = 0.5 MW/$P_{cluster}$ = 0.1 MW, medium plant P_{PtG} = 2.5 MW/$P_{cluster}$ = 0.4 MW and large plant P_{PtG} = 5.0 MW/$P_{cluster}$ = 0.7 MW) are shown in Figure 6-25, Figure 6-26 and Figure 6-27, respectively. For all of them, the payback time is around 10 years.

Table 6-4: Summary of the cases presenting positive NPV (limit 10 MW)

Probability BM	Size PtG [MW]	Size microturbines [MW]	Δp
$\rho_{BM} = 1$	0.5	0.1	3
	1.0	0.1	
		0.2	
	1.5	0.2	
		0.3	
	2.5	0.3	
		0.4	
		0.5	
	5	0.6	
		0.7	
		0.8	
		0.9	

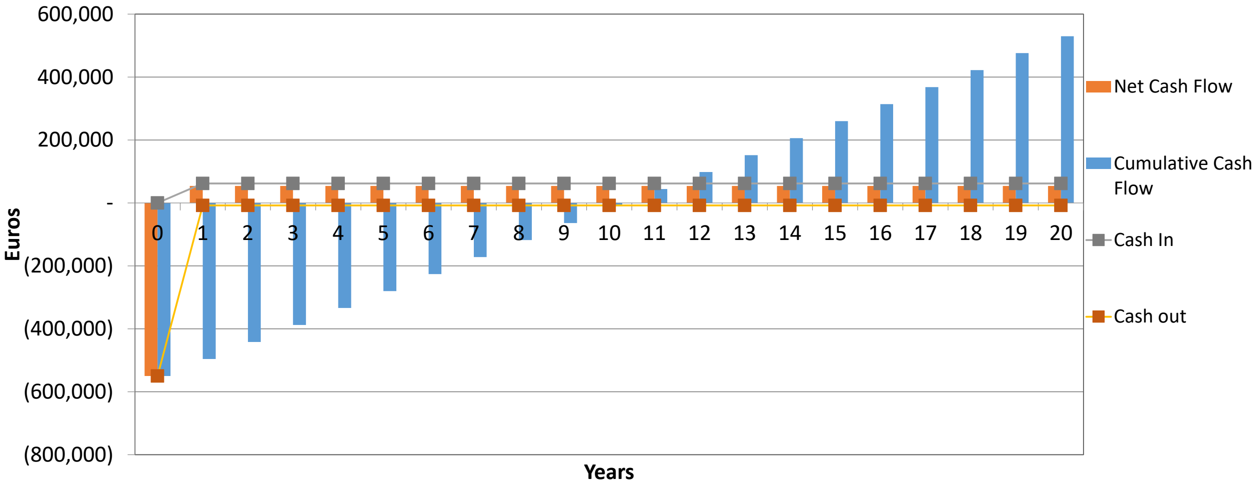


Figure 6-25: Business plan for the application under analysis with P_{PtG} = 0.5 MW/$P_{cluster}$ = 0.1 MW

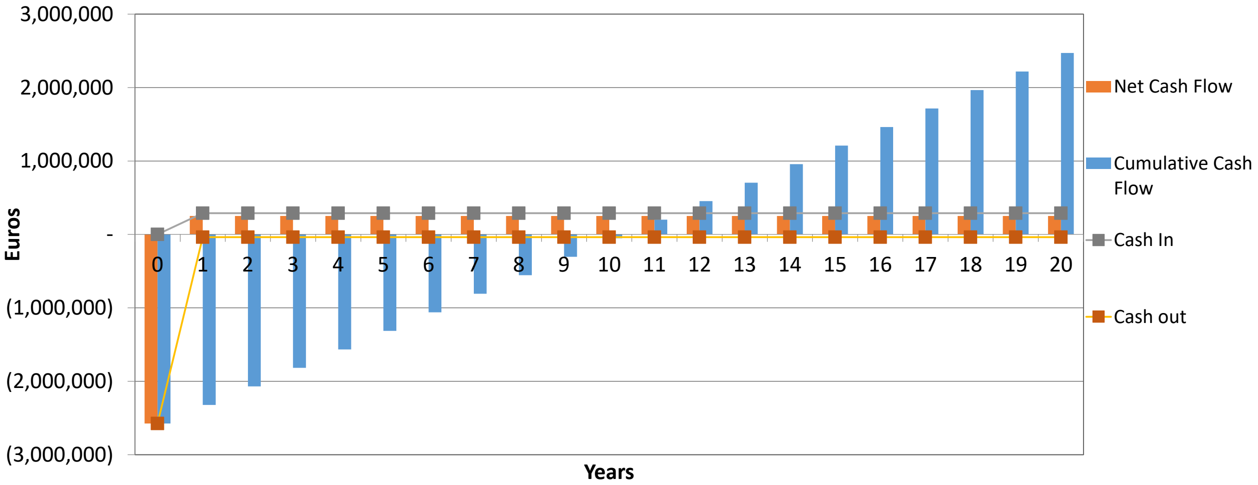


Figure 6-26: Business plan for the application under analysis with P_{PtG} = 2.5 MW/$P_{cluster}$ = 0.4 MW.

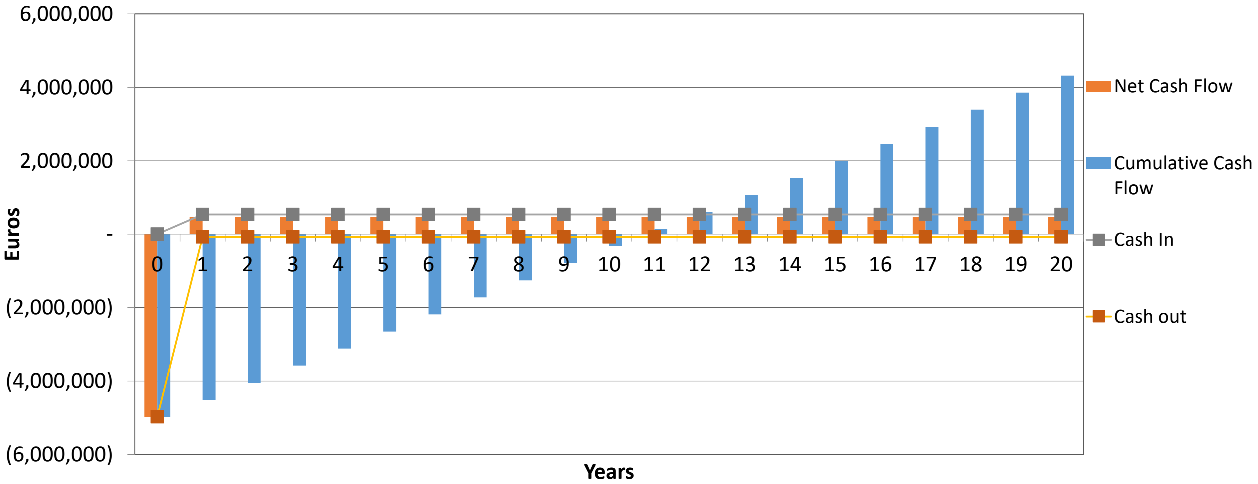


Figure 6-27: Business plan for the application under analysis with P_{PtG}= 5.0 MW/$P_{cluster}$ = 0.7 MW.

7 Technical and legislative aspects of using of SNG in gas turbines

7.1 Legislation

The legislation regarding the process of production of SNG takes into account the risk of having stored gas in the area of the plant. In this section, Italy is analysed, by referring to the European directives adopted in the Italian legislation.

In particular, the European directive 2012/18/UE [95] indicates the amount of substances (lower bound and higher bound[14]), which force the plant to adopt the measures for avoiding major hazards involving dangerous substances. For a PtG plant (also associated to a CCGT), it is necessary i) to understand which gases are stored, ii) to evaluate their hazard potential (e.g., if they are flammable or toxic) and iii) to estimate the quantity eventually stored.

As example, Table 7-1 lists the limits for H_2, natural gas and Liquefied Petroleum Gas (LPG).

Table 7-1: Indications of the maximum amount of stored gas [95]

Dangerous Substances	Lower-tier requirements [t]	Upper-tier requirements [t]
Hydrogen	5	50
Liquefied flammable gases (including LPG)**	50	200

** - Upgraded biogas

For the purpose of the implementation of this Directive, upgraded biogas may be classified under entry 18 of Part 2 of Annex I where it has been processed in accordance with applicable standards for purified and upgraded biogas ensuring a quality equivalent to that of natural gas, including the content of Methane, and which has a maximum of 1 % Oxygen.

As it is possible to see from Table 7-1, the two main gases treated in the PtG plant, i.e. hydrogen (in the case of Troia pilot) and flammable gas (for example LPG), are listed, and limits that require the application of this directive are reported. Therefore, for amounts higher than 5 tons for hydrogen and higher than 50 tons for flammable gas, directive 2012/18/EU [95] shall be applied. It is clear that the overall amount of those gases in the site shall be taken into account, considering also existing applications.

[14] The two limits implies different measures to be implemented

By focusing on the use of SNG for supplying gas-fired power plants, the legislation in Italy is essentially based on the D. Lgs. 152/2006 [96], which transfers the following European Directive in the Italian legislation:

- Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment [97]

- Directive 2003/35/EC of the European Parliament and of the council of 26 May 2003 providing for public participation in respect of the drawing up of certain plans and programmes relating to the environment and amending with regard to public participation and access to justice Council Directives 85/337/EEC and 96/61/EC [98]

The use of SNG is allowed, but it is necessary to remain under the emission limits. Among other fuels, natural gas can be used in a CCGT, but the technical characteristics of the natural gas are not specified (page 390 of the Annex of [96]).

Referring to the European rules, two different EU directives are devoted to indicate different rules in case of different (thermal) power:

- Directive (EU) 2015/2193 of the European Parliament and of the Council of 25 November 2015 on the limitation of emissions of certain pollutants into the air from medium combustion plants, treating the pollutants emitted by Medium Combustion Plants (MCP), with thermal power lower than 50 MW [99] (the values for NO_x and CO are shown in Table 7-2).

- Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) (Recast), treating the pollutants emitted by Large Combustion Plants (MCP), with thermal power higher than 50 MW [100].

These two directives shall be taken into account in order to evaluate if the fired fuel has a composition compatible with the maximum emissions. However, national laws shall be considered because limits can be lower. As example, in emissions limits for some types of large combustion plants are reported.

Table 7-2: Indications of the emission limits for NO_x and CO [99]

Emission limit values (mg/Nm^3) for NO_x and CO for gas fired combustion plants

	NO_x	CO
Combustion plants firing natural gas with the exception of gas turbines and gas engines	100	100
Combustion plants firing blast furnace gas, coke oven gas or low calorific gases from gasification of refinery residues, with the exception of gas turbines and gas engines	200 (4)	—
Combustion plants firing other gases, with the exception of gas turbines and gas engines	200 (4)	—
Gas turbines (including CCGT), using natural gas (1) as fuel	50 (2) (3)	100
Gas turbines (including CCGT), using other gases as fuel	120	—
Gas engines	100	100

Notes:

(1) Natural gas is naturally occurring methane with not more than 20 % (by volume) of inerts and other constituents.

(2) 75 mg/Nm^3 in the following cases, where the efficiency of the gas turbine is determined at ISO base load conditions:
- (i) gas turbines, used in combined heat and power systems having an overall efficiency greater than 75 %;
- (ii) gas turbines used in combined cycle plants having an annual average overall electrical efficiency greater than 55 %;
- (iii) gas turbines for mechanical drives.

(3) For single cycle gas turbines not falling into any of the categories mentioned under note (2), but having an efficiency greater than 35 % – determined at ISO base load conditions – the emission limit value for NO_x shall be $50x\eta/35$ where η is the gas turbine efficiency at ISO base load conditions expressed as a percentage.

(4) 300 mg/Nm^3 for such combustion plants with a total rated thermal input not exceeding 500 MW which were granted a permit before 27 November 2002 or the operators of which had submitted a complete application for a permit before that date, provided that the plant was put into operation no later than 27 November 2003.

In the Directive 2010/75 EU there is not a clear reference to the concentration of SO_2 in the case natural gas is fired in gas turbines and gas engines. Concentration of sulphur in feeding gas should be taken into account.

7.2 Technical constraints

Natural gas is the desired fuel for gas turbines, but this fuel must be clean dry gas, especially for an advanced-technology gas turbine. This condition is necessary because the Dry Low NO_x Combustors (DLNOCs) are very sensitive to any liquid carry-over into the combustor, which leads to failures due to flashback problems in these combustors.

This requires the gas to be clean and heated to ensure the fuel gas would meet the requirements of the gas turbine Original Equipment Manufacturer[15] (OEM).

The DLNOCs require very dry gas: moisture is undesirable because it can combine with methane and other hydrocarbons to generate solids in the form of hydrates.

Variation in the heating value as a result of gas phase composition variation affects gas turbine emissions, output, and combustor stability. Changes greater than 10% require gas control hardware modifications. Variation in heating value could be an issue if it occurs daily or weekly: in this situation,

[15] The specifications need to be provided by the manufacturers

the user should ensure that the variations are within the value allowed by the gas turbine OEM. Many of the large power plants have on-line instruments that determine and monitor heating values for both the good of the turbine and in some cases the purchase of fuel gas is based on the heating value rather than the volume of gas.

Table 7-3 and Table 7-4 describe the composition the fuel must comply with according to OEM specifications. In order to evaluate if the synthesis natural gas produced with the PtG plant can be used to feed a gas turbine, it is necessary to evaluate the fuel consumption.

All the analyses performed in WP 6 have been done considering a heavy-duty gas turbine with a gross power at the generator of 270 MW_{el}, whose data is reported in Table 7-5.

Table 7-3: Gas fuel specifications (General)

Fuel properties	Max	Min	Notes
Lower heating value [Btu/lb]	1,150	300	Guidelines only
Modified Wobbe Index – range	+5%	–5%	$WI = LHV/\sqrt{S_{p.Gr} \cdot T_f}$[16]
Flammability		>2.2:1	Rich to lean fuel to air ratio, volume basis
Gas constituent	**Max**	**Min**	**% vol**
Methane	100	85	% reactant species
Ethane	15	0	% reactant species
Propane	15	0	% reactant species
Butane + Paraffin (C_4 +)	5	0	% reactant species
Hexane (C_6)	0.5	0	
Hydrogen	0	0	% reactant species
Carbon monoxide	15	0	% reactant species
Oxygen	10	0	% reactant species
Carbone dioxide	15	0	% total (reactants + inerts)
Nitrogen	30	0	% total (reactants + inerts)
Sulfur	< 1%	-	
Total inerts	30	0	T_f > 300 °F possibility of gum formation if excess aromatics are present

[16] *WI* = Wobbe Index, *Sp.Gr* = Specific Gravity, T_f =flame temperature

Table 7-4: Gas fuel specification according to gas turbine OEM

Fuel properties	Max	Min	Notes
Lower heating value [kJ/kg]	50,056	40,000	Max value defined as 100% methane
Tolerance on LHV	+5%	–5%	
Gradient of variation	0.1%/s	–	Defined as dLHV/dt
Wobbe Index [MJ/√(kg m^3)]	37.6 + 16.0%	37.6 – 16.0%	
Gas constituents limits			
Hydrogen sulfide (H_2S)	≤ 10		ppm (weight)
Hydrogen (H_2)	≤ 1		% by volume – mandatory limit

Table 7-5: Data of turbine used in all WP 6 analyses

	Unit	Base load
Fuel	–	Natural gas
Lower heating value	kJ/kg	46,253
Gross power at the generator	MW	270
Fuel consumption	kg/s	14.98

8 Conclusions

During the last years, the introduction of large amounts of RES-based power plants has introduced a number of new challenges, due to the impossibility to dispatch these plants properly. This fact has a number of consequences, and among them the necessity of new forms of storage is the most prominent.

Among the different sectors of the electricity system, this report mainly focused on the generation side. In particular, thanks to the expertise provided by one of the partners involved, the coupling of CHP plants and PtG plants has been deeply investigated. One of the main results is that the presence of market rules not matching with the nature of PtG can make the expansion of the technology difficult. In fact, the application facing the unbalances of a gas-fired power plant highlights that, even if the PtG works properly in terms of unbalance recovery, the use of PtG takes a disadvantage from the way in which the TSO provides penalties/benefits. Also the use of PtG as a means for providing capacity downward shows some critical points, due to the low price of the product (i.e., SNG) and the efficiency of the chain, which cannot justify the use of electricity produced by fossil fuel for producing SNG.

In case of electricity produced by RES-based power plants, the use of PtG is more convenient (because the electricity converted comes from free primary energy source), but the need to have a reasonable payback time implies the presence of incentives with all the electricity European markets considered (in all the countries analysed it has to be at least 60 €/MWh).

The investigation of the possibility to use PtG coupled with a cluster of microturbines can be a potential application, which can allow having a possible use of PtG as it helps to move towards a 100% RES-based electricity system. The convenience of this approach is strongly depending on the excess of RES to be converted, as well as the price of the electricity in the balancing market. Of course, the use of SNG as fuel for gas-fired turbines needs the fulfilment of both the environmental limitations and the technical constraints of the turbines, mostly based on the amount of H_2 present in SNG and water, which can create issues to the proper operation of the machine.

The possible applications of PtG are not limited to the generation side, and this fact has been proven by the literature review made. By relating the papers found with the general framework introduced, different new applications can be found to be interesting to be investigated in the next stages of the project:

- The use of PtG for supporting the electrical network operation is particularly interesting when the networks experience congestions due to excess of RES installed. In that case, PtG can help to alleviate the electrical network problems, and defer the investment on the network structure reinforcements.

- The use of PtG fits well with the necessity of seasonal storage, which is one of the main characteristics that a future electricity system mainly based on RES power plants has to have for being robust enough (the installation of PtG on transmission level can help to reach this level of robustness).

- At distribution level, an operation control strategy involving different types of storage (and among them PtG) can provide the means for avoiding typical problems due to the installation of large shares of RES, for example overvoltages and reverse power flow.

- In any case, the introduction of an overall optimal management strategy based on a joint analysis of both electrical and gas network seems to be the best option for creating an optimal management strategy involving different assets.

- The possible application for creating prosumers both on the electrical and gas sides has to be investigated, but the size of the electrolyser and the methanation, and their costs have to be carefully considered for allowing the diffusion of the technology at the customer level.

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