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STORE&GO

Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimisation

D6.6

Report on the impact of PtG on selected scenarios

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Dissemination level

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	RE	Restricted to a group specified by the consortium (including the Commission Services)
	CO	Confidential, only for members of the consortium (including the Commission Services)

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Table of Contents

Executive Summary

This Deliverable presents the results obtained by investigating the interaction between the future electricity transmission system and the Power-to-Gas (PtG) technology.

The work done is based on the code shown in D6.4 “Report on the model of the power system with PtG”, which has been improved by introducing a meta-heuristic method (i.e., a customized genetic algorithm), which allows to decrease the computational time of the network solver.

The investments forecast to be applied on the transmission system (obtained by the Ten Years Development Plan 2018 of ENTSO_E [1]) comprises about 75 billion euros of network investments up to 2040.

A part of these investments (16 billion euros representing about 20% of the total amount) were shifted from network infrastructure to PtG in our simulations.

The cost of the PtG plants were determined in previous work by Work Package 5 and Work Package 7. Two different investment costs, referring to 2040 and 2050 respectively, were considered here. Thus, by maintaining the amount of investment in PtG, two capacity values of PtG were obtained, i.e., 17 GW and 24 GW.

The positions of the PtG plants were obtained by considering as constraints the availability of CO_2 (provided by studies carried out in Work Package 8) and the availability of renewable energy sources (RES) imbalance, as shown in Figure A.

Figure A: Positions of the PtG plants

By considering two out of the three scenarios forecast by ENTSO-E for the year 2040 (i.e., 2040DG and 2040GCA [2]), the obtained impact of PtG on the network is not negligible and allows to improve in all cases the value of RES dispatched. The amount of dispatched RES was compared between two cases: (i) all network investments implemented, and (ii) 20% of the network investments redirected to PtG.

The results, reported in Table A and Table B, show that the investment in PtG allows an increase of the amount of RES dispatched at the European level. The increase lies in the range between 9% and 20%, depending on the month and the scenario considered.

Table A Increase of the RES dispatched in 2040 DG ENTSO_E scenario with 24 GW of PtG

	Total increase of dispatched RES in TWh		
	with PtG	**without PtG**	**increase in %**
January	172.2	157.5	9.4
April	133.9	119.9	11.7
July	126.3	108.7	16.2
October	114.4	104.3	9.7

Table B Increase of the RES dispatched in 2040 GCA ENTSO_E scenario with 24 GW of PtG

	Total increase of dispatched RES in TWh		
	with PtG	**without PtG**	**increase in %**
January	171.9	157.8	8.9
April	128.9	110.0	17.1
July	118.3	98.6	19.9
October	114.4	99.5	15.0

The presence of PtG in the European transmission system is beneficial also for its economic operation: in fact, as shown in Table C, the average electricity cost is decreasing between about 13 and 23% thanks to the increase of the share of RES injected into the system.

Table C: Average electricity cost with and without PtG

Scenario	Average electricity costs in €/MWh		
	NoPtG	**17 GW**	**24 GW**
2040 GCA	35.57	30.98 (-12.9%)	27.39 (-23.0%)
2040 DG	52.67	45.03 (-14.5%)	42.63 (-19.1%)

Acronyms

AEC-CAT	Alkaline Electrolysis – Catalytic methanation
DAM	Day-Ahead Market
DCOPF	DC Optimal Power Flow
DG	Distributed Generation
DUOPF	DC Unit de-commitment Optimal Power Flow
ENTSO_E	European Network of Transmission System Operators for Electricity
GA	Genetic Algorithm
GCA	Global Climate Actions
GDP	Gross Domestic Product
mpc	Matpower Case-file
PEMEC-CAT	Proton Exchange Membrane Electrolysis – Catalytic methanation
PtG	Power-to-Gas
PV	Photovoltaic
RES	Renewable Energy Sources
ROR	Run-On-River plant (hydro power plant)
SNG	Synthetic Natural Gas
ST	Sustainable Transition
TYNDP	Ten Year Network Development Plan

1 Introduction

The evaluation of the impact of Power-to-Gas (PtG) technology on electricity systems is an important aspect aiming to show the role that this technology can have to handle the non-predictability of non-dispatchable Renewable Energy Sources (RES).

In the next future, the share of electricity produced by RES will increase, and this will require a system with additional flexibility. In this sense, PtG can be one of the key technologies thanks to its capability to handle the excess of RES and to create as final product Synthetic Natural Gas (SNG), which can be stored (even for long time) into the existing gas network.

In the framework of the project STORE&GO [3], Work Package 6 (WP6) focused on the modelling and simulation of PtG into the electricity system, with the aim to highlight the contribution that PtG can have on network stabilisation in a long-term perspective.

The results of the research activities were reported in two Deliverables, i.e.:

- D6.1 "D6.1: Report on opportunities and options for PtG in power systems" [4], submitted in May 2017, and focusing on the conceptualisation of the role of PtG into the electricity system. In particular, this Deliverable contains a detailed analysis regarding potential applications of PtG into the electricity system, by presenting an approach highlighting the relations between the specific aspects (called dimensions) of the electricity system and the features of the PtG technology. Part of the work was also published in [5].

- D6.4 "Report on the model of the power system with PtG" [6], submitted in October 2018, and reporting the technicalities of the models used for the analysis. In particular, the report showed the models created for PtG plants (based on *real* measurements provided by the demo site of Falkenhagen), together with the network models used and all the technical details for properly representing the electrical aspects. Part of the work was published in [7]

Starting from the models used and presented in [6], and taking into account the long-term perspective of the project, this Deliverable aims to investigate the additional flexibility that PtG technology can add to the electricity system in some 2040 scenarios. These scenarios have been derived from the Ten Year Development Plan 2018 (TYNDP) [1] and are briefly summarised in Section 2.

Then, in Section 3 a summary of the main modelling aspects is reported, as a useful reminder of the different aspects defined into the code. Section 4 focuses on the siting and sizing of PtG plants, whereas Section 5 reports the results. Finally, Section 6 contains the concluding remarks.

2 Description of the scenarios ENTSO_E

The long-term perspective of the analysis implied the use of the most updated ENTSO_E scenarios taken from the TYNDP [1], summarised in Figure 2-1.

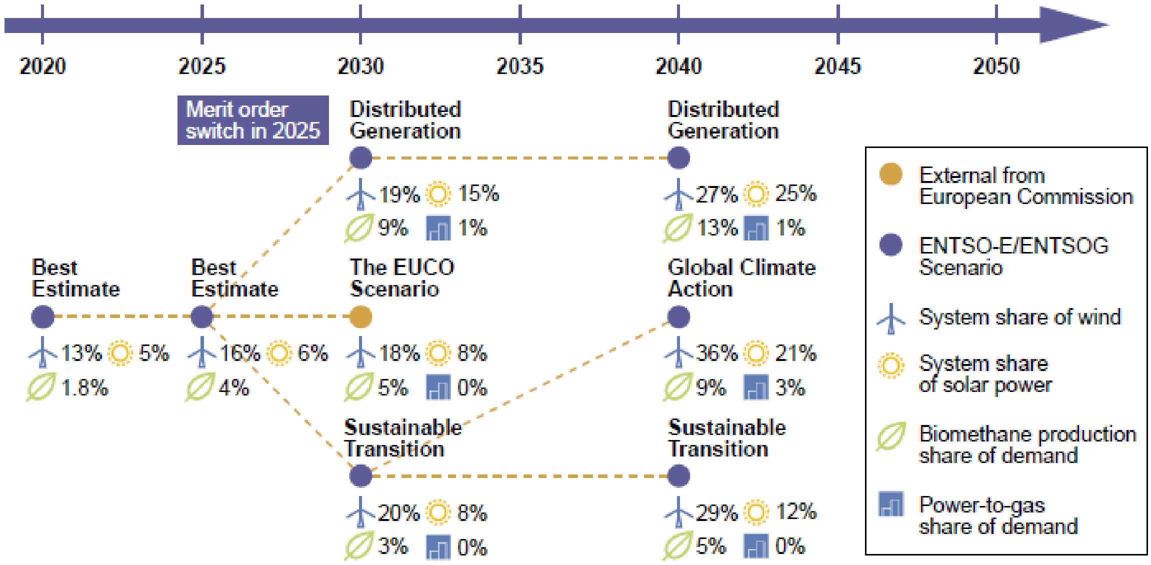

Figure 2-1: The scenario building framework for TYNDP 2018. RES share of demand for electricity and gas [2]

Three story lines were indicated as potential paths towards the year 2040:

- **Sustainable Transition (ST)**, where the CO_2 reduction is reached through the replacement of coal and lignite by gas in the power sector. Gas-fired power plants have a strong role, due to the relatively low price of the gas. Carbon capture is considered a valid option for industries.
- **Distributed Generation (DG)**, which considers the consumers as the centre of the entire energy strategy. More decentralised technology is taken into account, because of the reduction of the technology costs. System adequacy is guaranteed by a centralised system which provides enough peak capacity. The electricity demand increases in some sectors (such as heating and transport) but reduces in other (as in the residential sector).
- **Global Climate Actions (GCA)**, which represents the scenario where there is full engagement of the international community to dramatically reduce the CO_2 emissions. Particular emphasis is provided to the *large-scale* RES-based power plants. A CO_2 market is implemented and sends the correct market signals for low-carbon investments. The electricity growth is limited by the increase of the efficiency.

The load and generation characteristics of the three scenarios are shown in Figure 2-2, Figure 2-3 and Figure 2-4.

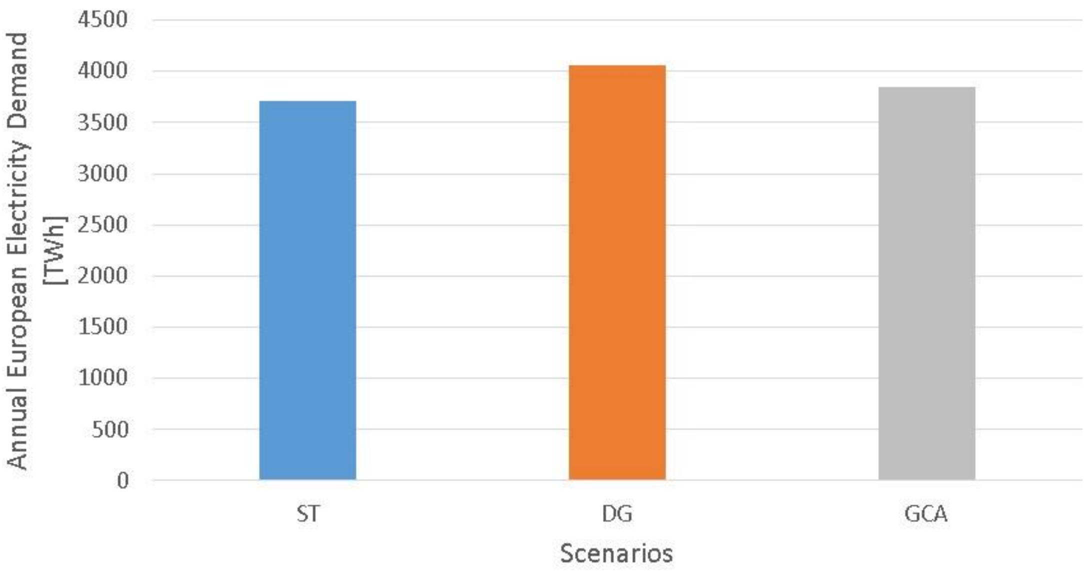

Figure 2-2: Annual European electricity demand for the three scenarios 2040

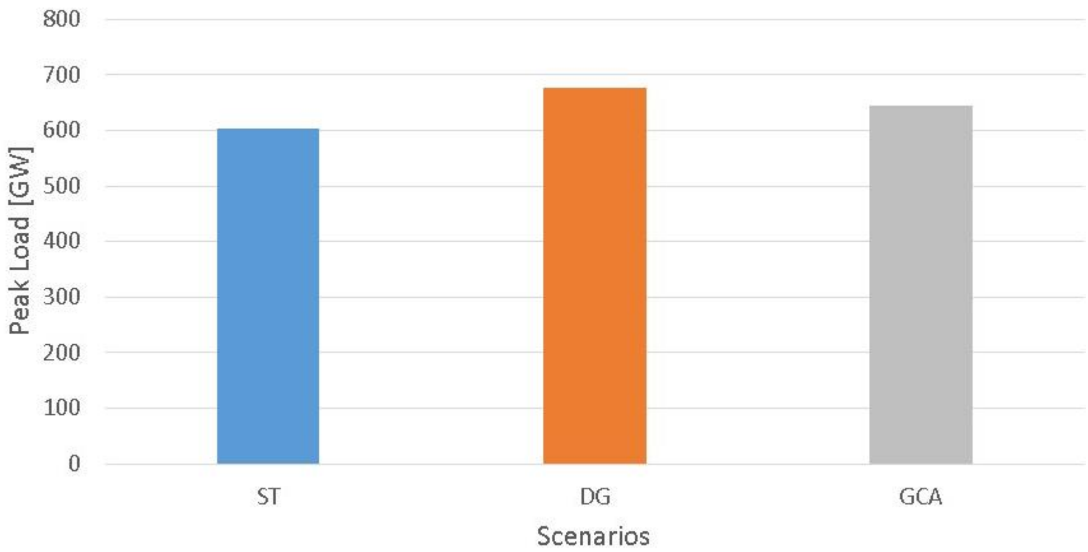

Figure 2-3: European electricity peak load of the three scenarios in 2040

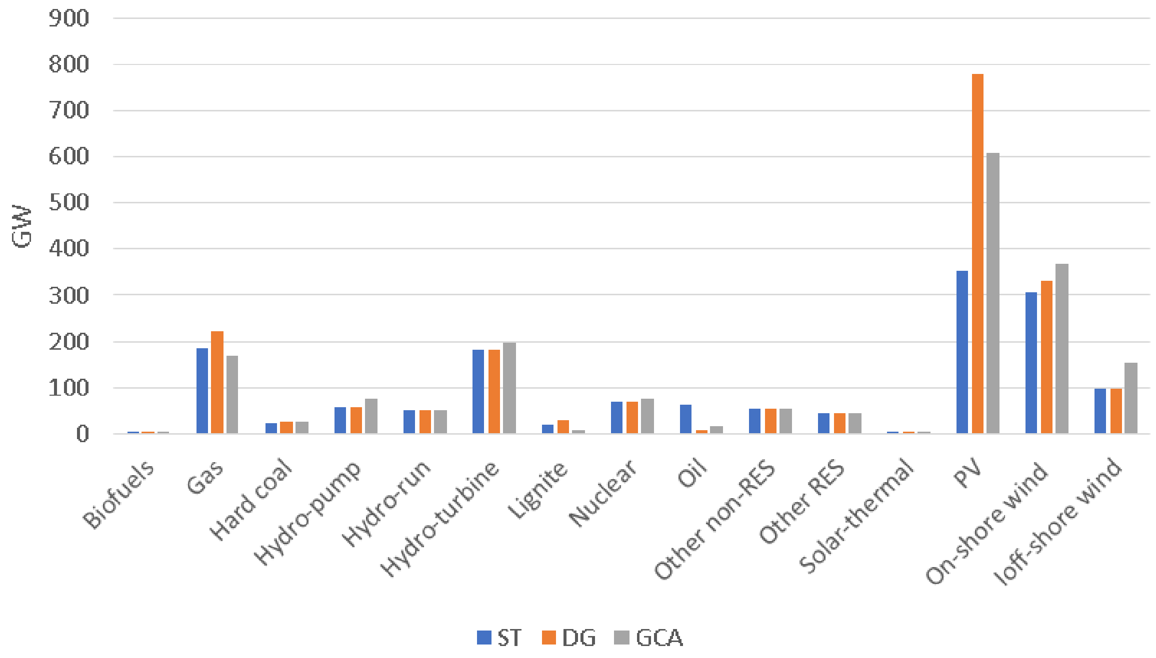

Figure 2-4 Generation capacity of the three scenarios.

It is shown that the two scenarios in which the PtG technology has more room to be successfully applied are the DG scenario and the GCA scenario, where the increase of RES is higher and the decarbonisation goals are stricter, as shown in Table 2-1.

Table 2-1 CO_2 emission and RES annual generation in the different scenarios [2]

Scenario	CO_2 emissions [Mtons]	RES annual generation [TWh]
2040ST	386.51	1,628.5
2040DG	379.50	2,280.4
2040GCA	207.81	2,336.6

Furthermore, according to the source [2] for these two scenarios a non-negligible production of synthetic gas is expected. In fact, the production of synthetic gas is forecast to be between 1.1 and 2.5% of the total gas demand for DG and GCA scenarios, whereas the role of PtG is marginal in the ST scenario.

Table 2-2: Total gas demand and PtG contribution [2]

Scenario	Annual gas demand [TWh]	Contribution PtG [%]	Contribution PtG [TWh]
2040ST	4919.6	0.0	0.0
2040DG	4224.8	1.1	46.5
2040GCA	3901.3	2.5	97.5

For these reasons, the next analysis will be carried out by considering as main scenarios the GCA and the DG.

3 Summary of the code characteristics

As previously mentioned, this Deliverable is based on the modelling part described in D6.4 [6]. For this reason, this section aims to recall the principal characteristics of the model, and the improvement made with respect to the first release, both in terms of modelling and computational time.

3.1 Network information

The model considers in the network #T3 reported in [6] and taken from [8]. For the convenience of the reader, the representation of the network is shown in Figure 3-1.

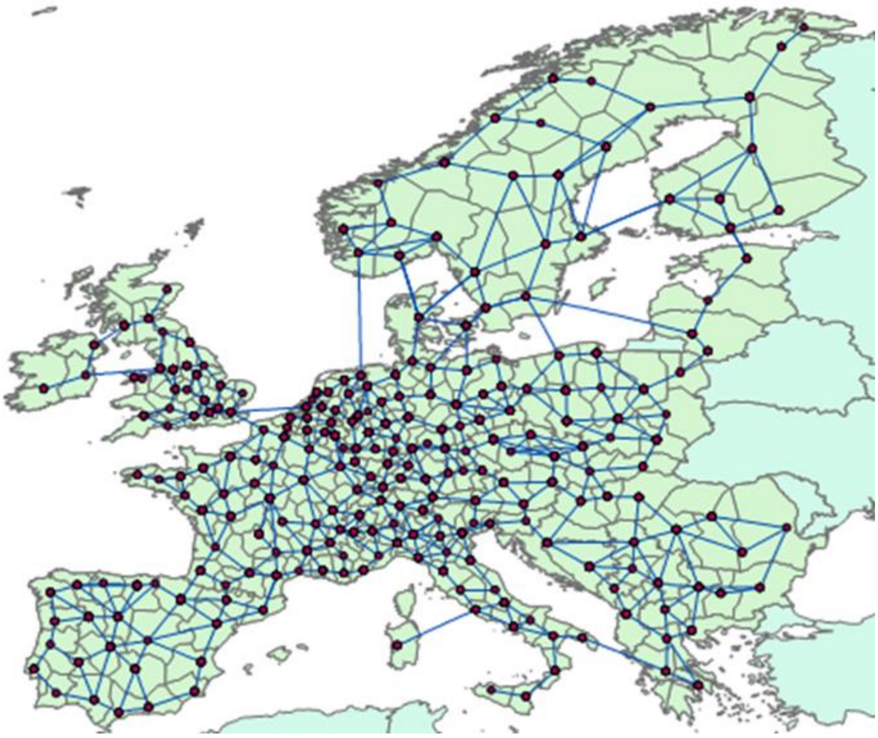

Figure 3-1: Figure of the simplified European network

It covers all the ENTSO_E countries: Albania (AL), Austria (AT), Bosnia and Herzegovina (BA), Belgium (BE), Bulgaria (BG), Estonia (EE), Finland (FI), Croatia (HR), Czech Republic (CZ), Denmark (DK), France (FR), Germany (GE), Great Britain (GB), Greece (GR), Hungary (HU), Ireland (IE), Italy (IT), Latvia (LV), Lithuania (LT), Luxembourg (LU), Montenegro (ME), The former Yugoslav Republic of Macedonia (MK), Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Romania (RO), Serbia (RS), Slovakia (SK), Slovenia (SI), Spain (SP), Sweden (SE) and Switzerland (CH).

It is composed of 256 nodes, and every node is representative of a *cluster*, obtained by applying a *k*-means clustering techniques to the entire EU transmission network. As a simplification, all the connections among the clusters are represented through an equivalent 380 kV line, which considers also the transfer capacity due to lines operated at lower voltage. The line parameters refer to a well-defined standard line configuration and are shown in Table 3.3 of [6]. The number of branches are in total 460 (operated in AC), whereas 24 lines are operated in DC (with the technology HVDC).

The number of generators is 828, whereas the total load is about 360 GW. The summary of the network characteristic is shown in Table 3-1.

Table 3-1: Summary of the main network characteristics

Buses	Branches	DC lines	Generators	Load [GW]
257	460	24	828	~360

The share of load for every cluster was obtained by considering a combination between the population and Gross Domestic Product (GDP) of each cluster.

Both the original load profiles referred to the year 2013, as well as the installed generation power: have been updated according to the information of the ENTSO_E scenario. Specific aspects of the RES have been addressed, summarised in Section 3.2.

3.2 RES aspects

3.2.1 PV production

The installed PV capacity data was gathered from the EMHIRES dataset [9], provided by the Strategic Energy Technologies Information System (SETIS). The EMHIRES dataset provides information about PV installed capacity at country level, by bidding zone, at NUTS 1 level and at NUTS 2 level. By assigning each bus to the corresponding NUTS 2 region it is possible to reach the highest level of spatial resolution available with this dataset.

The EMHIRES dataset also provides 30 years of hourly production levels, for each one of the previous spatial resolutions. However, this information is only enough for hourly analyses, so another source is needed in order to study the network at a higher temporal resolution. This was achieved by using Bright's solar model [10]: this model, at given points coordinates, simulates a *yearly irradiance* profile (and not directly the power) with a temporal resolution of one minute that can be averaged according to the user's need. Starting from the irradiance and by applying the formulation shown in [11], the energy obtained from PV was then calculated.

3.2.2 Wind production

Since the EMHIRES dataset provides for the wind generation the same information as given for the PV generation, this source was also used for characterising the wind in Europe.

However, also in this case another source of information is necessary to add variability to the average value of production. Due to the absence of an analogous simulator as [10] for wind, an original approach has been developed, for taking into account the variability of the wind starting from real measurements coming from large wind power systems.

In this way a profile closer to the reality was obtained, as shown in Figure 3-2. It is worth to note that the use of this procedure allows to add a variable profile to the average one, which allows to emulate the real profile in a more proper way.

The effectiveness of the procedure was tested through an auto-correlation analysis whose sample can be found in [6].

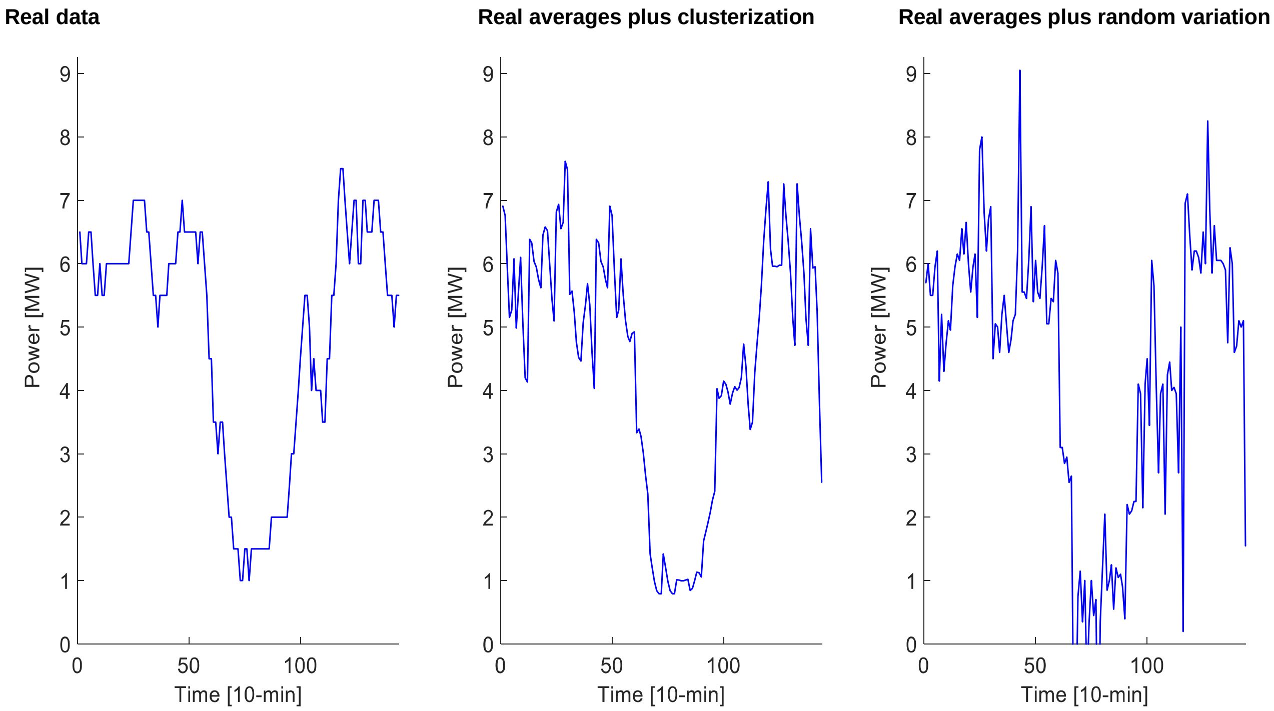

Figure 3-2: Wind profiles used in the autocorrelation test

3.2.3 Power-to-Gas

The model of PtG used is based on the measurements carried out on the alkaline electrolysis Falkenhagen plant, as detailed in [6]. The measurements are based on different power settings (see Figure 3-3) and the model allows also to properly take into account all the auxiliary services (pumps, compressors, and so on) which are needed for the correct operation of the plant.

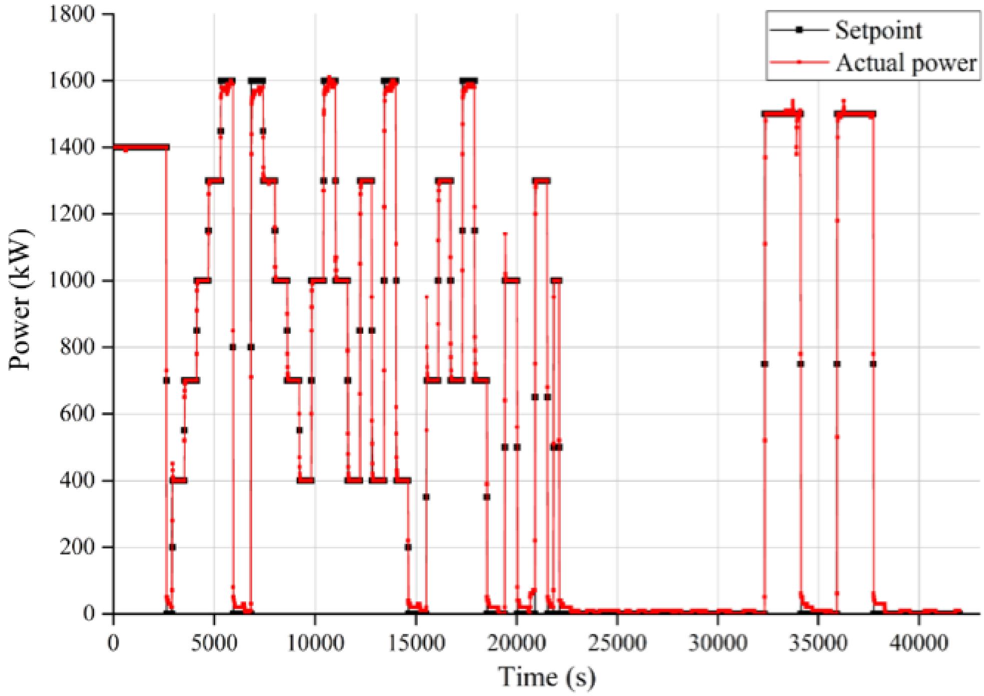

Figure 3-3 Falkenhagen test on an AEC-based electrolyser

3.3 Day-ahead and intra-day market

The PtG plants could operate as *balancing* element to face the RES production variation.

The model chosen to investigate this aspect uses a two-step formulation, where the first step aims to represent the day-ahead market through an hourly-based Optimal Power Flow (OPF), and on the results obtained an intraday OPF is solved.

The two above mentioned OPFs aim to find the set of generators allowing the operation of the system at minimum generation cost. In particular, the first OPF dispatches the expected value of RES and the traditional generation through an economic merit order, whereas the second one aims to redispatch the traditional generators and the PtG for facing the unbalances caused by the variable nature of the RES.

These two OPFs use as coding environment Matlab®, and recall the function that executes the OPF developed in Matpower [12]. The flowcharts of the two codes are shown in Figure 3-4. With respect to the previous version of the code, the computational time has been reduced by adding a genetic algorithm to the Unit Decommitment step. The unit decommitment is necessary to switch-off some of the generator to improve the objective function value by switching off the generators not strictly necessary to supply the load and with high cost at minimum power.

The unit-decommitment step was the one which, in the first release, took a considerable amount of time to be solved. This was due to the basic heuristics that was implemented, which made some repetitive tests by switching on and off the generation (basically the method was based on successive iterative improvements)

For overcoming this aspect and allowing a more complete analysis of the impact of PtG at the European level, the unit decommitment was improved by including a genetic algorithm and making an external loop recalling the main codes. This external loop aims to make possible the simulations of entire periods (e.g., entire months). The detail of the implementation of the genetic algorithm are shown in Appendix A, whereas the flowchart of the final version of the code have been included together with the implementation details in Appendix B.

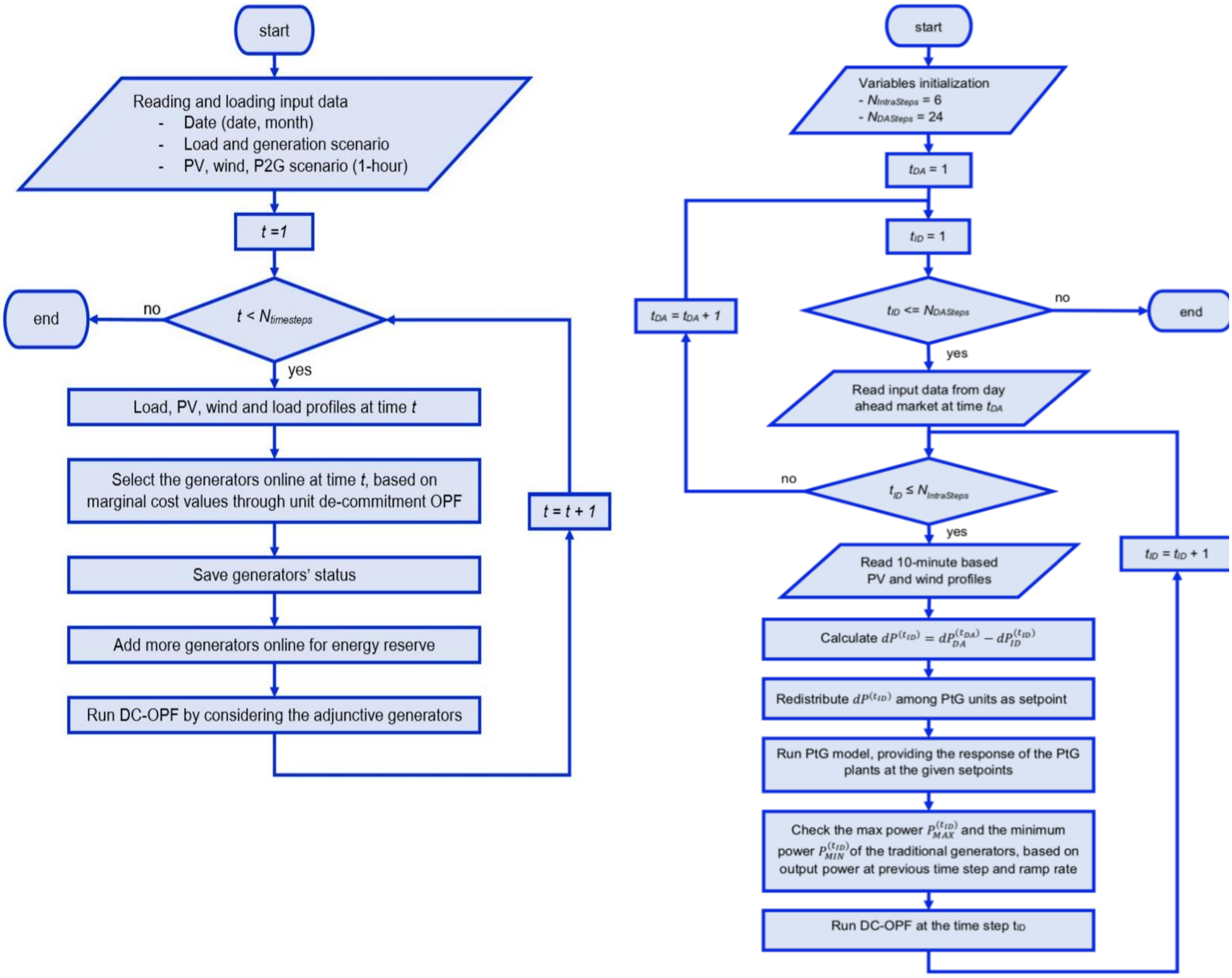

Figure 3-4: Flowcharts of the two codes [6]

4 Siting and sizing of PtG plants

4.1 Potential CO_2

The placement of the PtG units in one of the European clusters defined in Section 3.1 is highly dependent on the amount of CO_2 available in the surrounding area.

The characterization of the CO_2 potential was kindly provided by GWI (partner of the project), and, thanks to it, the areas more suitable for the installation were found. This information was based on D8.7 [13].

4.2 Network investments

With the aim of satisfying the energy demand of the near future and maintaining the system secure, ENTSO_E planned new investments to enhance transmission network, trying to solve issues affecting the network. The representation of the investments on the European map is shown in Figure 4-1.

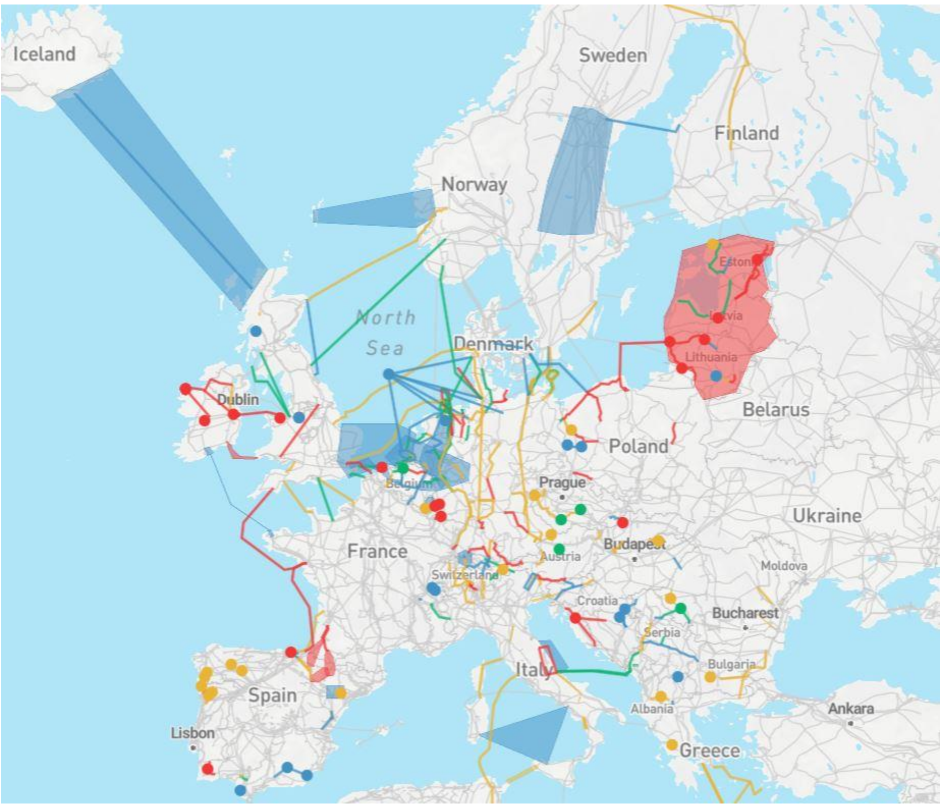

Figure 4-1: ENTSO_E's Project Map with 166 transmission and 15 storage projects. [1]

With the aim of the project all these investments were classified according to the year of construction, for properly updating the electrical system information.

In fact, the scope of the study was comparing the investment on network infrastructure and the potential investment in PtG technology, and understanding how the technology PtG could improve the flexibility of the system with respect to the sole investments in new lines.

The creation of the investment database took into account the enhancement grid plan to 2025, 2030 and 2040 based on [14], which essentially considers:

- The Pan European Market Modelling Database, from which the forecast of future network demand is derived.
- The Pan European Climate Database, which allows to assess the impact of climate years within the time and resource constraints of TYNDP 2018 timelines
- The System Needs, i.e., for obtaining the maximum value for European citizens by addressing the need of the continuous access to electricity all over Europe and the compliance with the objectives set out in the Climate Agenda for 2040.

Not all the investments reported in the created database were suitable to be included into the network model. In fact, based on the model shown in Figure 3-1 it is evident that the network model is composed of lines connecting the different clusters. If an investment refers to a line whose terminals fall in the same cluster, it cannot be included in the future system model. Thus, the database was analysed and the new lines were added to the map to check whether their total lengths were contained within a region or if the lines connected different regions.

The data of interest of the investments were the ID project and name, the costs of the project, length (in km), voltage level, type of the connection, starting and final points positions, capacity increase (measured in MW), status of the project, commissioning year and evolution driver.

The information regarding the network investments cover the time period up to 2040, and no further data is available for time horizon beyond 2040 from ENTSO_E TYNDP

The total amount of investment forecast to be applied to the European transmission system is about 75 billion euros.

The summary of the investments is shown in Table 4-1. Two cases were thus considered:

- Case 1: all the forecast investments are applied to strengthen the network
- Case 2: part of the investments (around 20%) are diverted towards PtG[1]

Table 4-1: Network investments forecast by ENTSO_E

Case No.	Network investments [M€$_{2018}$]	PtG investments [M€$_{2018}$]
1	59,699.44	15,981.12
2	75,680.56	-

The calculation of the capacity of PtG has been made according to the PtG CAPEX shown in Table 4-2, provided by WP5 and WP7.

The quantity of PtG power inserted into the simulations is derived by averaging the costs of the two technologies considered for 2040. This means that an average cost of 95 M€$_{2018}$ makes it possible to install 17 GW of PtG.

[1] This amount has been chosen because it provides the order of magnitude of the PtG capacity that could be reasonably financed.

Table 4-2: STORE&GO cost forecast for PtG plants

Year	**Cost per 100 MW unit [M€$_{2018}$]**	
	PEM electrolyser with catalytic methanation	Alkaline electrolyser with catalytic methanation
2040	80.15	110.7
2050	53.50	77.0

Furthermore, the costs in 2050 were also applied to the same amount of investment shifted from network to PtG technology, providing 24 GW PtG capacity. This hypothesis was made for showing an optimistic case, involving a faster cost decrease of the technology. Both cases will be shown in Section 5.

5 Results

The results show three main points:

- PtG helps the dispatching of the renewables, by increasing the share of RES (with respect to the total forecast by ENTSO_E) that is possible to be dispatched.
- This dispatching is higher than the one that can be obtained by only installing new lines.
- The increase of the share of RES leads to a reduction of the average cost of electricity
- The two-step code is really helpful to highlight the potential of PtG as a flexibility tool, and thus this kind of approach should be considered for this kind of study.

It is important to clarify that the installation of RES plants does not guarantee *a priori* their dispatch, i.e., the presence of the network can lead to cut part of the RES generation. In the following, the results show that the installation of PtG allows to alleviate this issue.

The position of the PtG plants has been found according to 1) the availability of CO_2 in the different clusters and 2) the amount of RES that, due to the presence of the network constraints, cannot be completely dispatched.

The placement of the PtG plants considered in the following analysis is shown in Figure 5-1.

Figure 5-1: Positions of the PtG plants

The distribution of the capacity among the countries is shown in Table 5-1 and in Table 5-2.

Table 5-1: Distribution of the capacity among the countries (case 17 GW)

Country	P_n [GW]
Austria	1
Belgium	1
Denmark	0.1
France	0.5
Germany	5
Italy	3.4
Netherlands	1
Spain	3
Switzerland	1
United Kingdom	1

Table 5-2: Distribution of the capacity among the countries (case 24 GW)

Country	P_n [GW]
Austria	1
Belgium	1
Denmark	0.3
France	0.7
Germany	8.8
Italy	4.6
Netherlands	1.2
Spain	4
Switzerland	1.2
United Kingdom	1.3

5.1 Scenario GCA, PtG=17 GW

The results of the application of the real time market are quite interesting: in fact, in all the months analysed (i.e., January, April, July and October) the presence of PtG helps the dispatch of the RES, by improving the amount of energy produced by them that can be injected in the network (as shown from Figure 5-2 to Figure 5-4). The increase of RES is summarised in

Table 5-3: depending on the different types of RES, the increase of dispatched RES with respect to the value obtained by using only network infrastructure is at least 7.4% and arrives up to 18.7%.

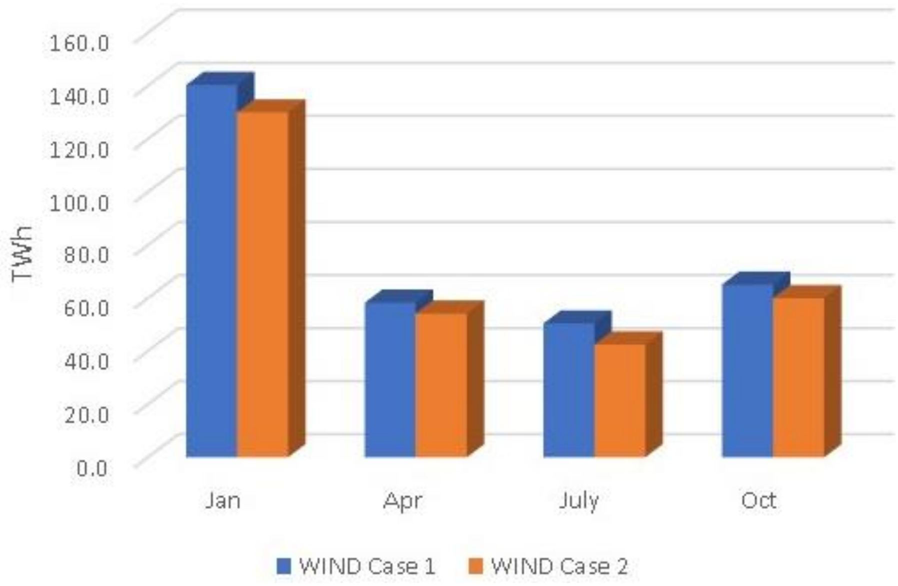

Figure 5-2: Wind dispatched in 2040 GCA scenario.
Blue: Case 1, with 17 GW of PtG
Orange: Case 2, only network investments without PtG

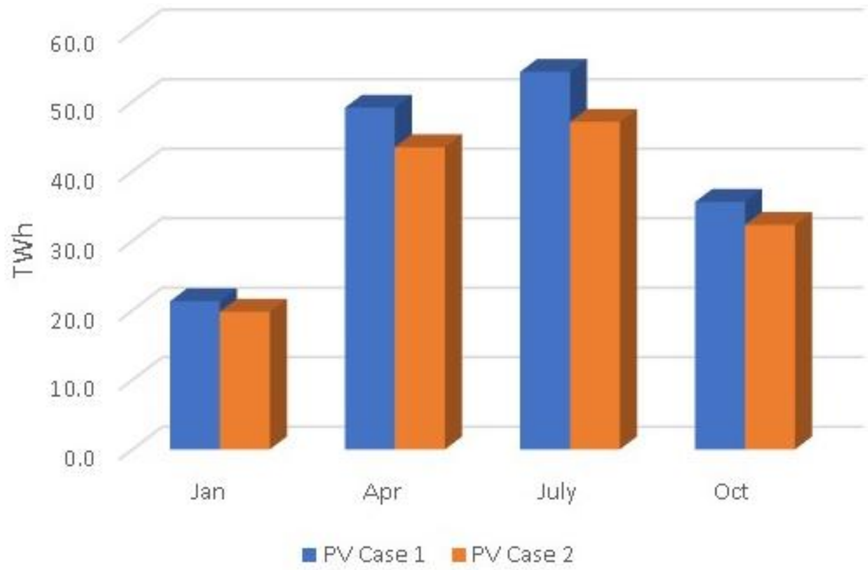

Figure 5-3: PV dispatched in 2040 GCA scenario.
Blue: Case 1, with 17 GW of PtG
Orange: Case 2, only network investments without PtG

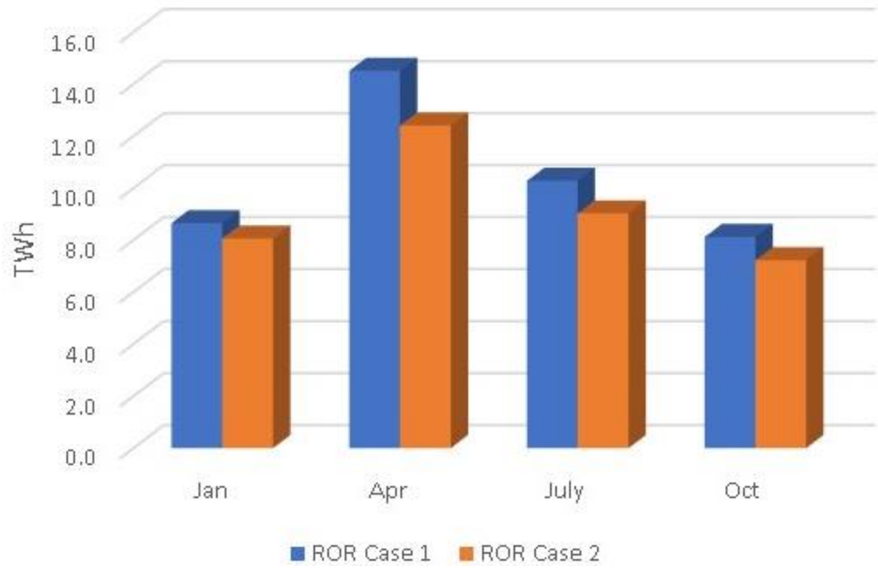

Figure 5-4: ROR[2] dispatched in 2040 GCA scenario.
Blue: Case 1, with 17 GW of PtG
Orange: Case 2, only network investments without PtG

[2] ROR: Run-of-the-river: indicates hydro power plants without hydro storage capability

Table 5-3: Comparison between the values of RES dispatched with (Case 1) and without (Case 2) 17 GW PtG in 2040 GCA scenario

	January	April	July	October
		WIND [TWh]		
Case 1 (with PtG)	140.4	58.3	50.5	65.1
Case 2 (without PtG)	130.0	54.2	42.5	60.0
increase [%]	8.0	7.6	18.7	8.5
		PV [TWh]		
Case 1 (with PtG)	21.3	49.1	54.3	35.6
Case 2 (without PtG)	19.8	43.5	47.1	32.3
increase [%]	7.7	13.1	15.3	10.3
		ROR [TWh]		
Case 1 (with PtG)	8.7	14.5	10.3	8.1
Case 2 (without PtG)	8.1	12.4	9.0	7.2
increase [%]	7.4	17.0	13.9	12.4

The total RES production is visualised in Figure 5-5, and, as detailed in Table 5-4, the increase of the total amount of RES production dispatched after the installation of PtG is about 10%.

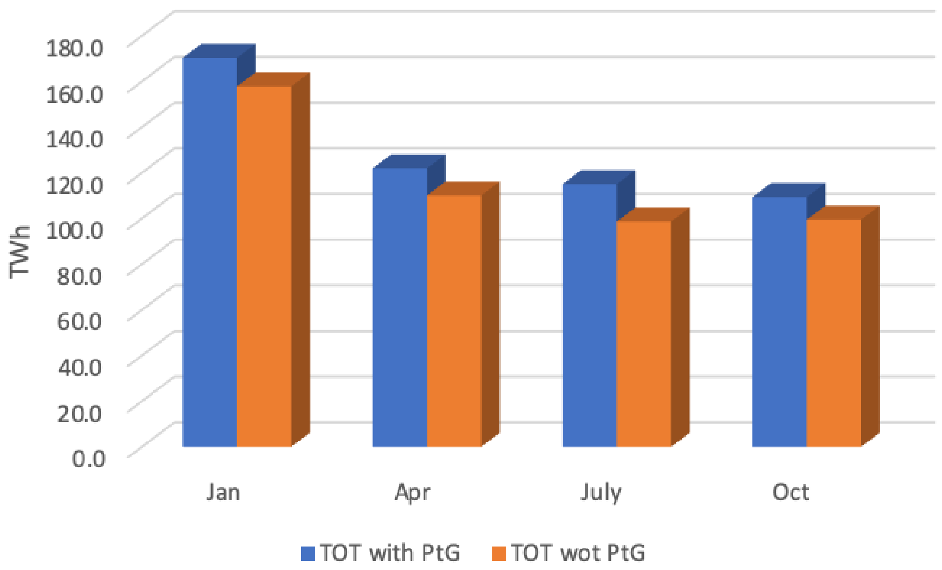

Figure 5-5: Total RES dispatched in 2040 GCA scenario.
Blue: Case 1, with 17 GW of PtG
Orange: Case 2, only network investments without PtG

Table 5-4: Increase of the RES dispatched in 2040 GCA scenario with 17 GW of PtG

	Total increase of dispatched RES [TWh]		
	with PtG	without PtG	increase [%]
January	170.3	157.8	7.9
April	121.9	110.0	10.8
July	115.0	98.6	16.6
October	109.4	99.5	10.0

It is worth to note that the use of the two-step code is useful to understand the effectiveness of the installation of PtG, because it highlights its potential in following the RES variability. In fact, considering PtG as a fixed load does not properly represent the real potential, because by considering PtG as a normal and fixed load, the potential increase varied between 2.4% and 4%, depending if the PtG was considered working at 60% or 100% of its nominal power.

The new energy dispatched consequently increases the share of RES (forecast by ENTSO_E) actually dispatched in the network, as shown in Table 5-5.

Table 5-5: Dispatched RES with respect to the available RES of by ENTSO_E 2040 GCA scenario with 17 GW of PtG

	RES available [TWh]	RES dispatched			
		without PtG [TWh]	%	with PtG [TWh]	%
January	241.1	157.8	65.5	170.3	70.7
April	196.3	110.0	56.1	121.9	62.1
July	189.0	98.6	52.2	115.0	60.9
October	158.0	99.5	63.0	109.4	69.2

It is worth to note that the values of RES available are in line with the once indicated in [2]: in fact, by considering each end month representative for its own season, the annual value of RES obtained from the simulation is 2352 TWh, which is not far from the corresponding value of the GCA scenario reported in Table 2-1.

5.2 Scenario GCA, PtG=24 GW

By considering the PtG plant cost forecast in 2050, with the same investment it could be possible to increase the capacity of PtG up to 24 GW. This value has been installed in the same node as before, and the results are shown from Figure 5-6 to Figure 5-9. The details regarding the increase of the different types of RES is shown in Table 5-6: as expected, the additional capacity of PtG installed improves the performance of the network, by increasing the value of RES energy dispatched. The increase of the overall RES production is shown in Table 5-7: the increase lies in the range between 8.9 and almost 20%, depending on the month.

Table 5-8 compares the amount of dispatched RES with respect to the values forecast from ENTSO_E. In all the months considered the installation of PtG allows to bring the share of dispatched energy higher than 60%, and by reaching as maximum 72% of the value forecast by ENTSO_E, whereas the use of the network 2040 allows to reach at maximum 65%).

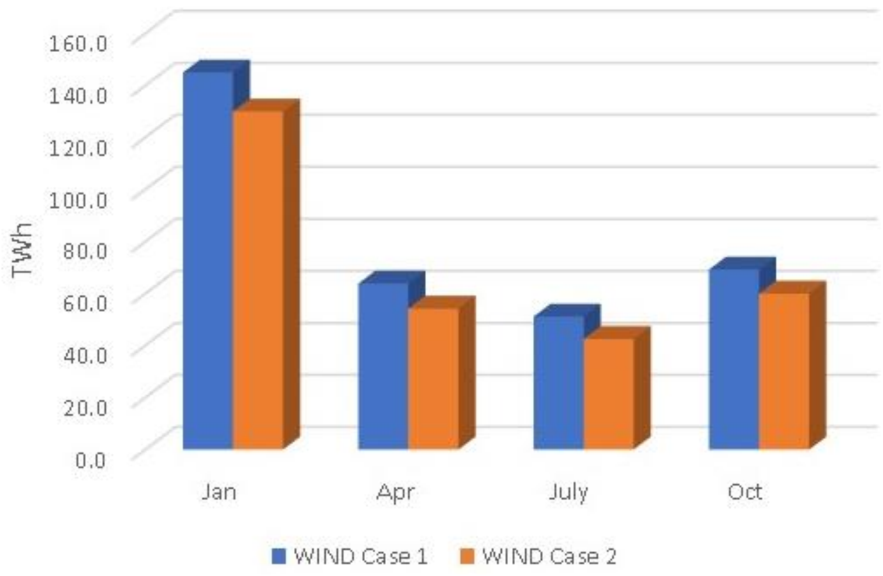

Figure 5-6: Wind dispatched in 2040 GCA scenario.
Blue: Case 1, with 24 GW of PtG;
Orange: Case 2, only network investments without PtG

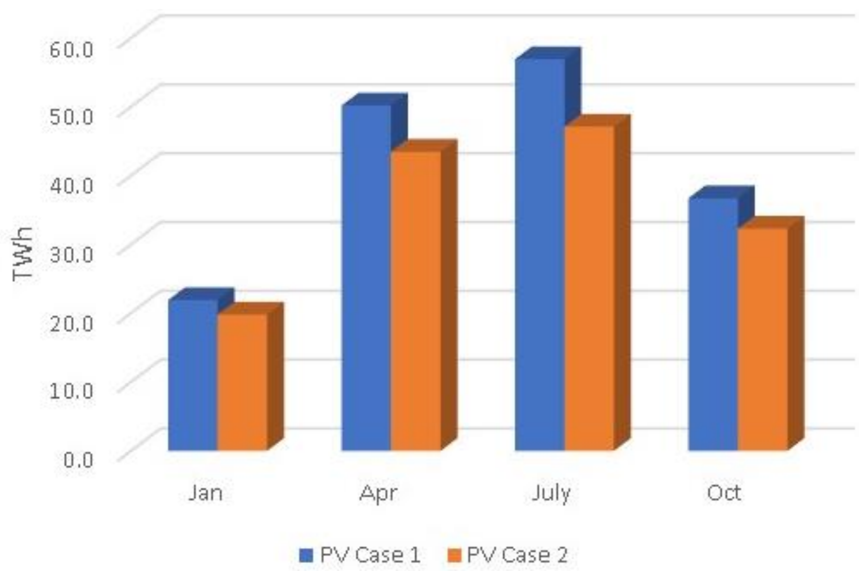

Figure 5-7: PV dispatched in 2040 GCA scenario.
Blue: Case 1, with 24 GW of PtG;
Orange: Case 2, only network investments without PtG

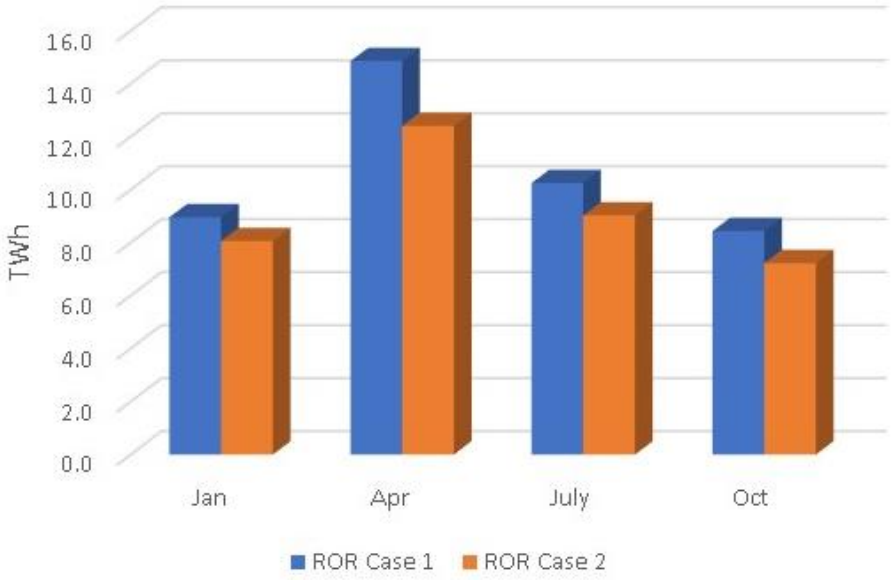

Figure 5-8: ROR dispatched in 2040 GCA scenario.
Blue: Case 1, with 24 GW of PtG;
Orange: Case 2, only network investments without PtG

Table 5-6: Comparison between the values of RES dispatched with (Case 1) and without (Case 2) 24 GW PtG in 2040 GCA scenario

	January	April	July	October
		WIND [TWh]		
Case 1(with PtG)	145.0	63.8	51.1	69.2
Case 2 (without PtG)	130.0	54.2	42.5	60.0
increase [%]	11.5	17.8	20.3	15.4
		PV [TWh]		
Case 1(with PtG)	21.9	50.2	56.9	36.7
Case 2 (without PtG)	19.8	43.5	47.1	32.3
increase [%]	10.7	15.5	20.8	13.7
		ROR [TWh]		
Case 1(with PtG)	9.0	14.9	10.2	8.4
Case 2 (without PtG)	8.1	12.4	9.0	7.2
increase [%]	11.1	19.8	13.5	16.8

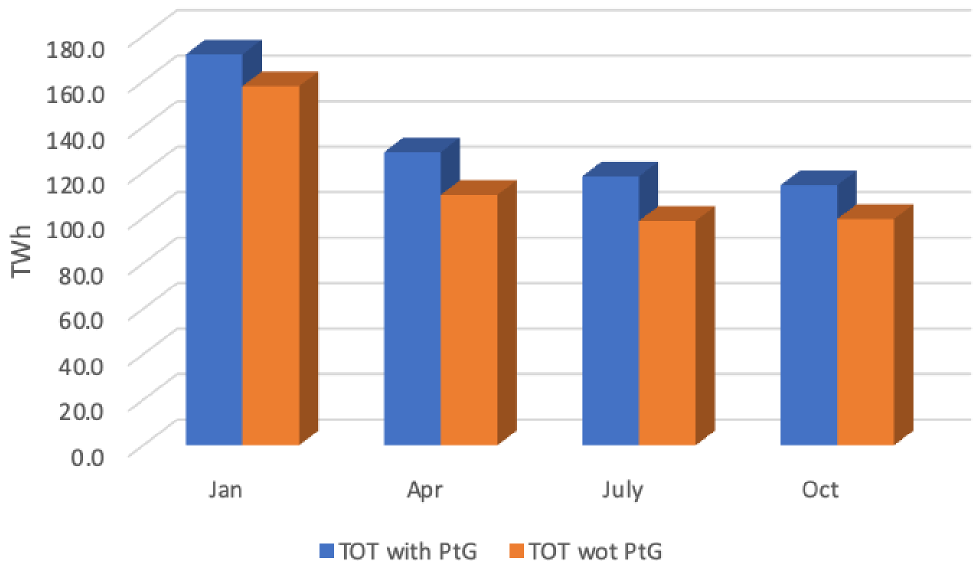

Figure 5-9: Total RES dispatched in 2040 GCA scenario.
Blue: Case 1, with 24 GW of PtG;
Orange: Case 2, only network investments without PtG

Table 5-7: Increase of the RES dispatched in 2040 GCA scenario with 24 GW of PtG

	Total increase of dispatched RES [TWh]		
	with PtG	without PtG	increase [%]
January	171.9	157.8	8.9
April	128.9	110.0	17.1
July	118.3	98.6	19.9
October	114.4	99.5	15.0

Table 5-8: Dispatched RES with respect to the available RES of ENTSO_E 2040 GCA scenario with 24 GW of PtG

	RES available [TWh]	RES dispatched			
		without PtG [TWh]	%	with PtG [TWh]	%
January	241.1	157.8	65.5	171.9	71.3
April	196.3	110.0	56.1	128.9	65.7
July	189.0	98.6	52.2	118.3	62.6
October	158.0	99.5	63.0	114.4	72.4

5.3 Scenario DG, PtG=17 GW

This scenario contains more PV than the GCA scenario, and consequently the availability of RES is higher during the summer. For understanding the performance of the geographical location analysed for GCA, the same geographical distribution was maintained also with this scenario. The impact of the PtG plants is shown from Figure 5-10 to Figure 5-12. The details regarding the dispatched amount of different RES types is reported in Table 5-9: as can be seen with the DG scenario, the installation of PtG is still helping the dispatching of RES, but the impact is slightly less compared to the GCA scenario, especially with reference to the ROR. This is due to the better performance reached by the DG network that implemented all the investments compared to the GCA scenario. In any case, the impact linked to the dispatching of PV and wind is aligned with the previous case and lie in the range ~7% to ~13%.

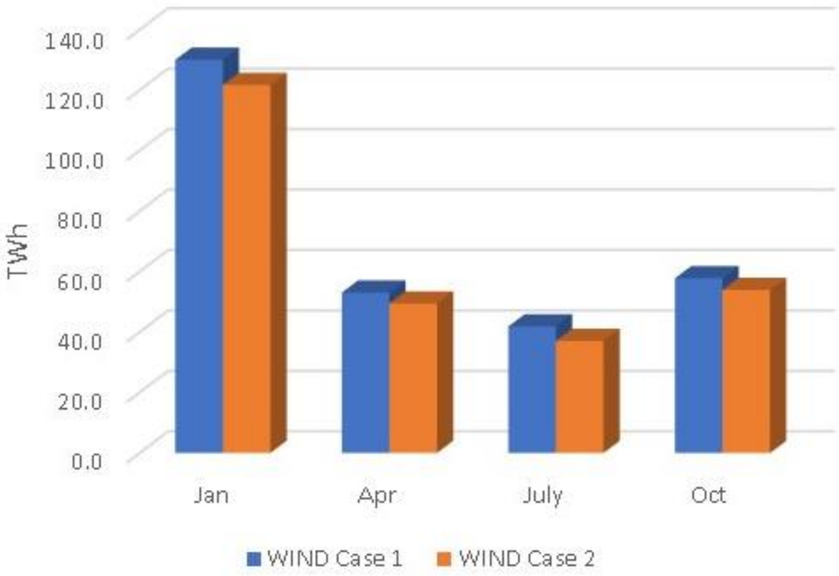

Figure 5-10: Wind dispatched in 2040DG scenario.
Blue: Case 1, with 17 GW of PtG
Orange: Case 2, only network investments without PtG

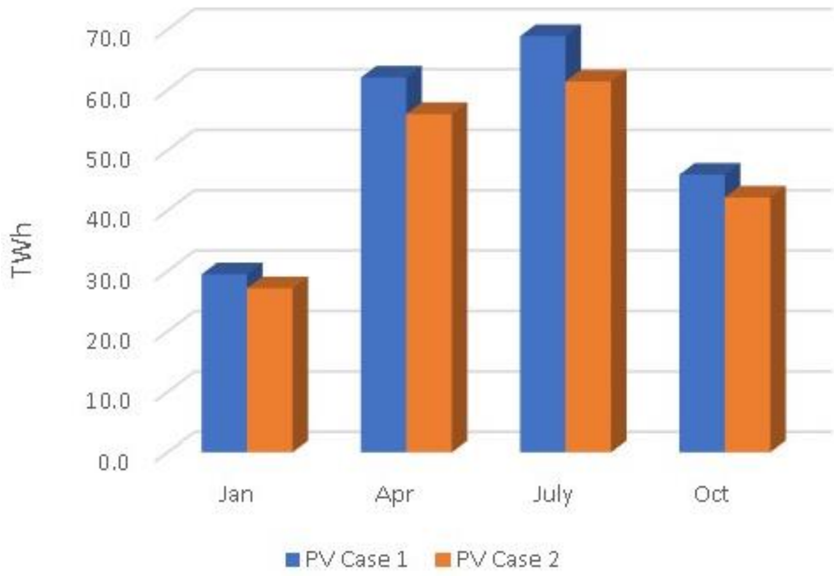

Figure 5-11: PV dispatched in 2040DG scenario.
Blue: Case 1, with 17 GW of PtG
Orange: Case 2, only network investments without PtG

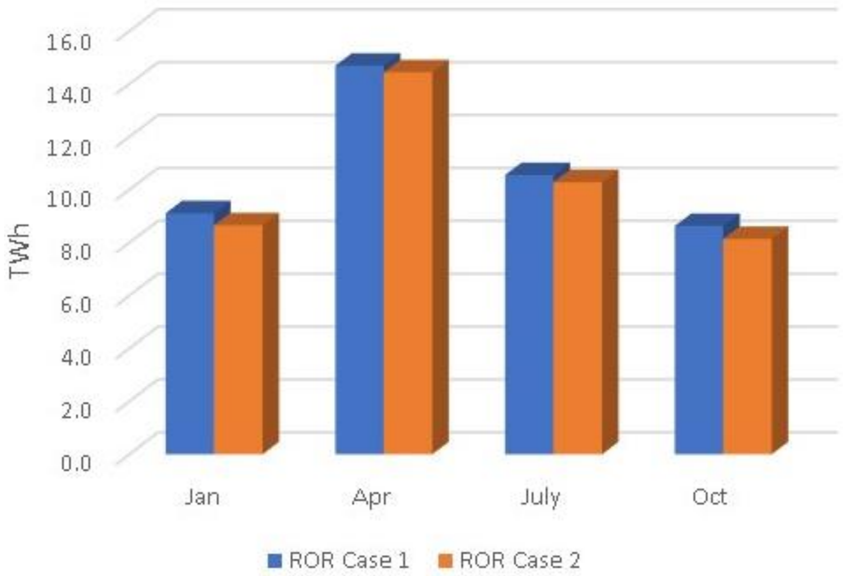

Figure 5-12: ROR dispatched in 2040DG scenario.
Blue: Case 1, with 17 GW of PtG
Orange: Case 2, only network investments without PtG

Table 5-9: Comparison between the values of RES dispatched with (Case 1) and without (Case 2) 17 GW PtG in 2040 DG scenario

	January	April	July	October
		WIND [TWh]		
Case 1 (with PtG)	130.1	53.0	41.8	57.8
Case 2 (without PtG)	121.7	49.4	37.1	53.9
increase [%]	6.9	7.3	12.2	7.1
		PV [TWh]		
Case 1 (with PtG)	29.5	62.0	68.9	46.0
Case 2 (without PtG)	27.2	56.0	61.4	42.2
increase [%]	8.6	10.8	12.9	9.0
		ROR [TWh]		
Case 1 (with PtG)	9.1	14.7	10.6	8.6
Case 2 (without PtG)	8.7	14.4	10.3	8.1
increase [%]	5.3	1.7	2.6	6.1

The results referring to the overall RES production are shown in Figure 5-13, and the details regarding the share increase are reported in Table 5-10. The increase of dispatched RES is in this case higher than 7% and reaches a maximum of about 12% compared to the case with all the network infrastructures installed. With respect to the values forecast by ENTSO_E, the installation of PtG allows to reach a minimum share of dispatched RES around 56% in July, and a maximum of around 71% in January, as shown in Table 5-11.

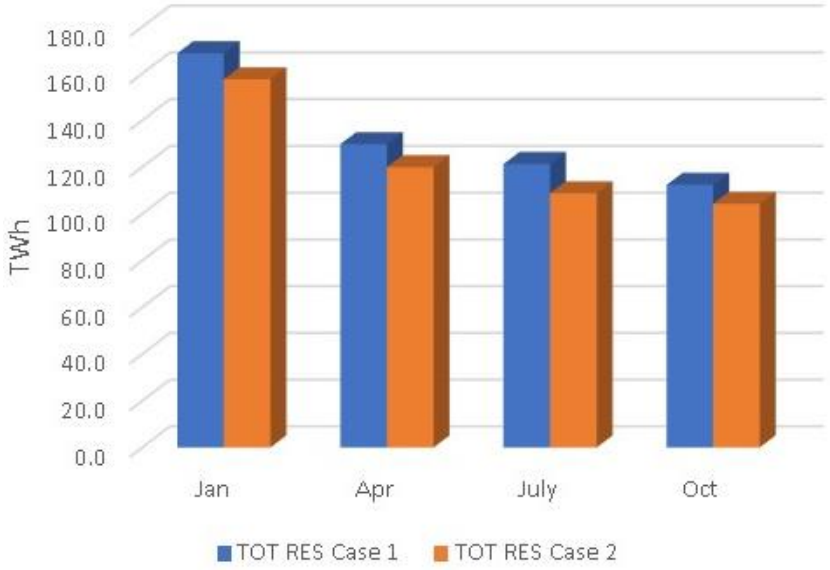

Figure 5-13: Total RES dispatched in 2040DG scenario.
Blue: Case 1, with 17 GW of PtG
Orange: Case 2, only network investments without PtG

Table 5-10: Increase of the RES dispatched in 2040 DG scenario with 17 GW of PtG

	Total increase of dispatched RES [TWh]		
	with PtG	**without PtG**	**increase [%]**
January	168.7	157.5	7.1
April	129.8	119.9	8.2
July	121.3	108.7	11.5
October	112.4	104.3	7.8

Table 5-11: Dispatched RES with respect to the available RES of ENTSO_E 2040 DG scenario with 17 GW of PtG

	RES available [TWh]	RES dispatched			
		without PtG [TWh]	**%**	**with PtG [TWh]**	**%**
January	238.4	157.5	66.1	168.7	70.7
April	213.2	119.9	56.2	129.8	60.9
July	215.1	108.7	50.5	121.3	56.4
October	171.5	104.3	60.9	112.4	65.7

It is worth to note that the values of RES available are in line with the once indicated in [2]: in fact, by considering each month representative for the corresponding season, the annual value of RES obtained from the simulation is 2511 TWh, which is not far from the corresponding value of the DG scenario reported in Table 2 1.

5.4 Scenario DG, PtG=24 GW

By increasing the availability of PtG, the results improve, as shown from Figure 5-14 to Figure 5-16, and detailed for all the RES in Table 5-12. For the ROR the increase of dispatched energy in the case with PtG slightly improves compared to the case considering 17 GW, whereas for PV and wind the increase is sensible (the minimum improvement is 8.2% whereas with 17 GW was 7.1%).

By considering the overall production from RES, the increase of energy dispatched is higher than in the case with 17 GW and lies in the range between 9.4 and 16.2% (Table 5-13). This is also highlighted in Table 5-14, where the increase of the dispatched RES-based energy compared to the value provided by ENTSO_E goes up to 72% (in January) and a minimum value of about 59% in July.

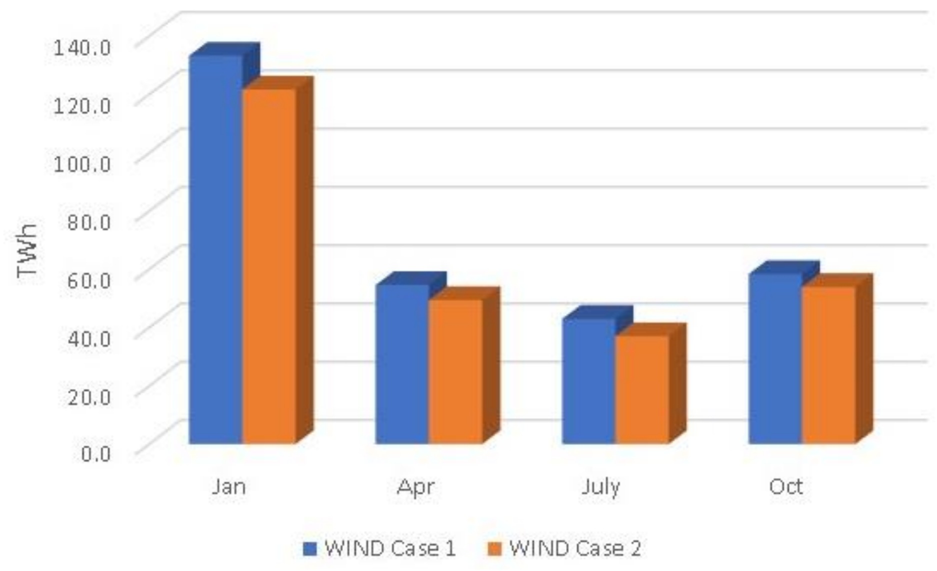

Figure 5-14: Wind dispatched in 2040DG scenario.
Blue: Case 1, with 24 GW of PtG
Orange: Case 2, only network investments without PtG

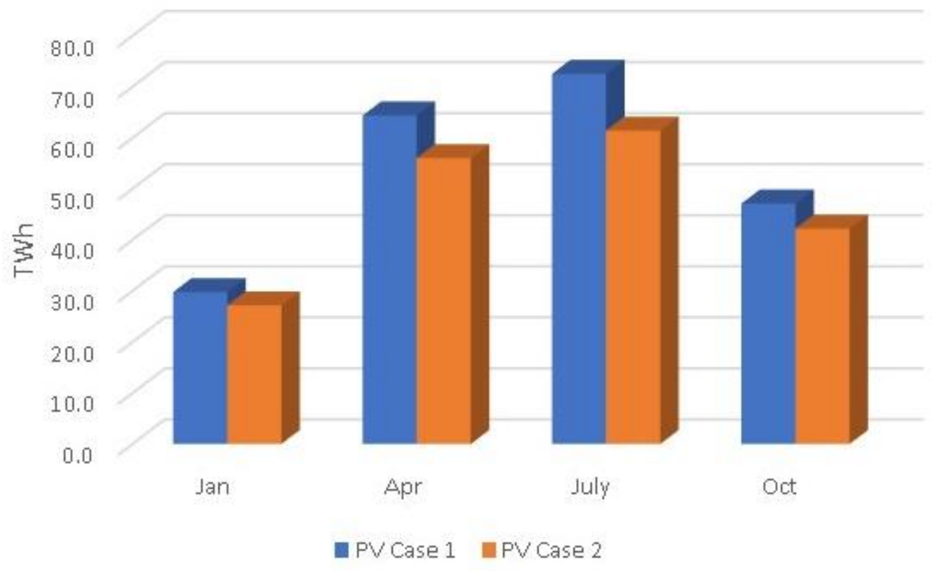

Figure 5-15: PV dispatched in 2040DG scenario.
Blue: Case 1, with 24 GW of PtG
Orange: Case 2, only network investments without PtG

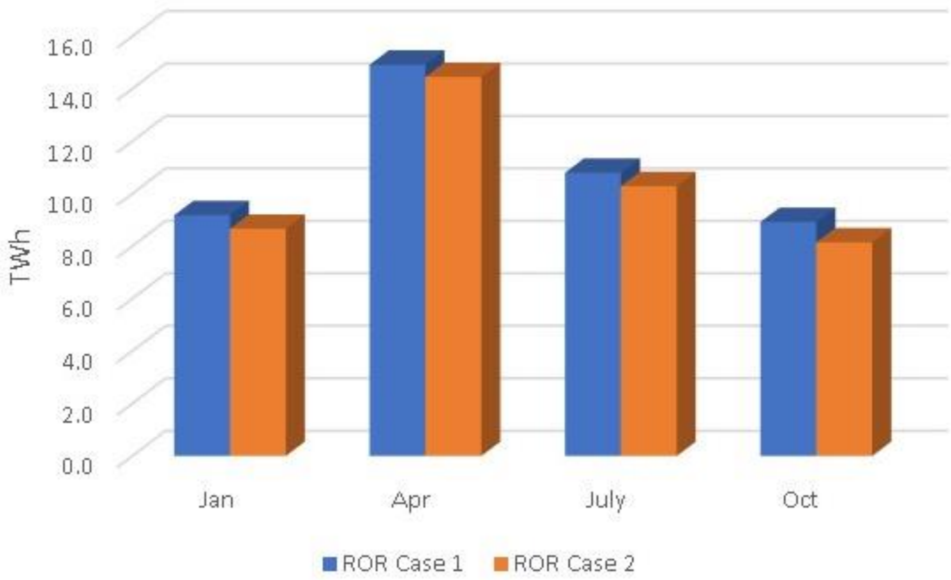

Figure 5-16: ROR dispatched in 2040DG scenario.
Blue: Case 1, with 24 GW of PtG
Orange: Case 2, only network investments without PtG

Table 5-12: Comparison between the values of RES dispatched with (Case 1) and without (Case 2) 24 GW PtG in 2040 DG scenario

	January	April	July	October
		WIND [TWh]		
Case 1 (with PtG)	133.3	54.6	43.0	58.4
Case 2 (without PtG)	121.7	49.4	37.1	53.9
increase [%]	9.5	10.5	16.0	8.2
		PV [TWh]		
Case 1 (with PtG)	29.8	64.4	72.5	47.1
Case 2 (without PtG)	27.2	56.0	61.4	42.2
increase [%]	9.6	14.9	18.1	11.7
		ROR [TWh]		
Case 1 (with PtG)	9.2	14.9	10.8	8.9
Case 2 (without PtG)	8.7	14.4	10.3	8.1
increase [%]	6.0	3.2	5.0	9.5

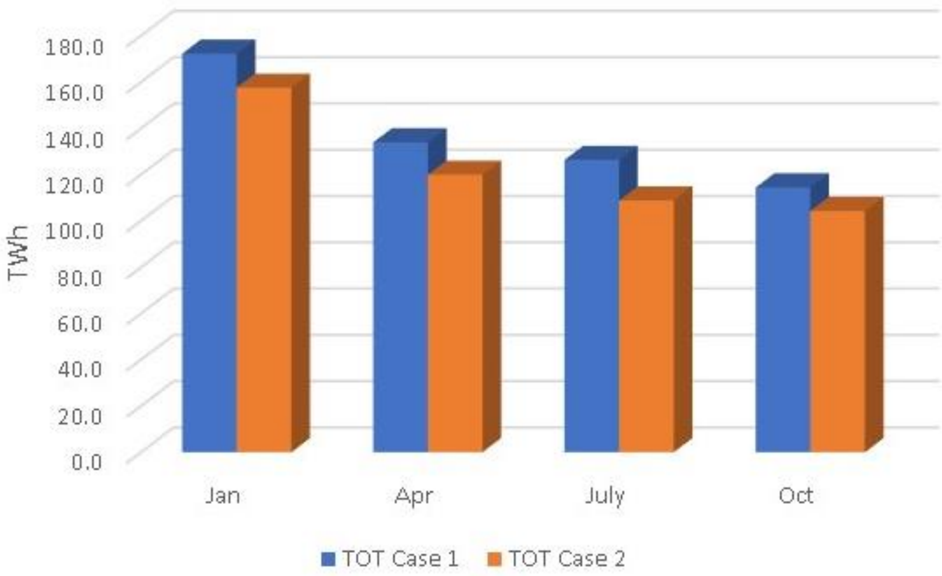

Figure 5-17: Total RES dispatched in 2040DG scenario.
Blue: Case 1, with 24 GW of PtG
Orange: Case 2, only network investments without PtG

Table 5-13: Increase of the RES dispatched in 2040DG scenario with 24 GW of PtG

	Total increase of dispatched RES [TWh]		
	with PtG	**without PtG**	**increase [%]**
January	172.2	157.5	9.4
April	133.9	119.9	11.7
July	126.3	108.7	16.2
October	114.4	104.3	9.7

Table 5-14: Dispatched RES with respect to available RES of ENTSO_E 2040 DG scenario with 24 GW of PtG

	RES available [TWh]	**RES dispatched**			
		without PtG [TWh]	**%**	**with PtG [TWh]**	**%**
January	238.42	157.51	66.0	172.2	72.2
April	213.2	119.9	56.2	133.9	62.8
July	215.1	108.7	50.5	126.3	58.7
October	171.0	104.3	60.9	114.4	66.9

5.5 System impact

From the system point of view, the installation of PtG is beneficial: in fact, as shown in Table 5-15, the average electricity cost reduces with the increase of the share of PtG. This is due to the fact that a higher value of RES is dispatched, which leads to a reduction of the overall system cost.

Table 5-15: Average electricity cost with and without PtG

Scenario	**Average electricity costs [€/MWh]**		
	without PtG	17 GW	24 GW
2040 GCA	35.57	30.98 (-12.9%)	27.39(-23.0%)
2040 DG	52.67	45.03(-14.5%)	42.63(-19.1%)

5.6 Synthetic Natural Gas production

From the work carried out in WP5, it has been obtained that the expected efficiency of the entire PtG chain in 2040 is 58.4% [15].

By considering that value of overall efficiency, the annual[3] electricity absorbed by the PtG plants, together with their equivalent working hours (obtained by dividing the electricity absorbed by the nominal power installed) is shown in Table 5-16.

Table 5-16: Annual absorbed electricity and equivalent working hours of the plants

Scenario	**Annual absorbed electicity [TWh/y]**		**Equivalent working hours [h]**	
	17 GW	24 GW	17 GW	24 GW
2040 GCA	144.13	205.80	8478	8575
2040 DG	144.00	205.72	8471	8572

Thus, the annual production of SNG for the analysed cases[3] was computed, and the results are shown in Table 5-17.

Table 5-17: SNG produced with 17 GW and 24 GW installed

Scenario	**SNG production [TWh/y]**	
	PtG 17 GW	PtG 24 GW
2040 GCA	83.60	119.36
2040 DG	83.52	119.32

It is worth to note that the produced SNG in the analysed cases is higher than the expected production from PtG in the scenario 2040 DG. Regarding the scenario 2040 GCA, the installation of 24 GW allows to overcome the expected production from PtG for that scenario, whereas the installation of 17 GW allows to reach a production slightly lower than that limit.

[3] The calculation was done considering each month representative of its own season

6 Conclusions

The work carried out so far aimed to investigate the potential of PtG to improve the flexibility of the electricity transmission system. A network with additional flexibility is required to allow the dispatch of a larger share of RES.

Two different ENTSO_E scenarios were considered. All the information regarding future network investments were collected and analysed to obtain an indication on how to update the network, and to identify the amount of investments that can be potentially shifted from network infrastructure to PtG infrastructure.

The results show that the PtG technology improves the network performance simply by adding new facilities. The improvement lies in the range between 9% and 20%, depending on the month and the scenario considered.

Furthermore, due to the increase of RES dispatched in the network in presence of PtG, the average electricity cost decreases in a range between 13% and 23%, depending on the scenario considered and the amount of PtG installed.

In addition, the installed capacity of PtG allows to reach the expected amount of SNG forecast by TYNDP in 3 out of 4 scenarios, thereby indicating that those capacities fit well with the overall objective expected in 2040.

These results, together with the low acceptance from the population of new electrical lines, make PtG a good candidate to reach the goals of decarbonising the energy sector through the increase of the share of RES, allowing also a reduction of the average cost of the electricity.

Appendix A: Implementation of the genetic algorithm

The genetic algorithm is an *evolutionary algorithm*, suitable for solving problems whose solution space surface is complex and characterised by a lot of local minima. The creation of the set of generators to be used for supplying the system is not trivial, and for this reason the genetic algorithm was chosen as the solution algorithm.

The genetic algorithm is a *population-based* method, and the components of the population are called *chromosomes*. They are composed of *genes*, whose value can be 0 (generator off) or 1 (generator on).

The step-by-step procedure is shown below:

1) Some generators are chosen as *potential candidates*: the potential candidates are the generators which are operating at minimum power and whose operation cost at that level of power is relatively high.

2) Among them, a percentage (the less expensive) is not considered as candidate, and the list is then updated, and now it is composed of N_g elements. These elements represent the genes which compose every chromosome

3) The initial population is created randomly, i.e., the initial status of the generators is randomly initialised.

4) At this point the genetic operators are applied to the initial population. This means the application of two operators called *crossover* and *mutation* to the initial population, to update the population according to the value of the objective function.

5) The algorithm continues up to one of the stop criteria is reached. The first stop criterion is based on the successive number of iteration showing a variation lower than a threshold of the objective function. This criterion is called *adaptive criterion*. On the other hand, a last resource criterion, based on the maximum number of iterations, is added.

Crossover

The crossover allows to mix the genes belonging to two different chromosomes, by creating two children (called also *offsprings*).

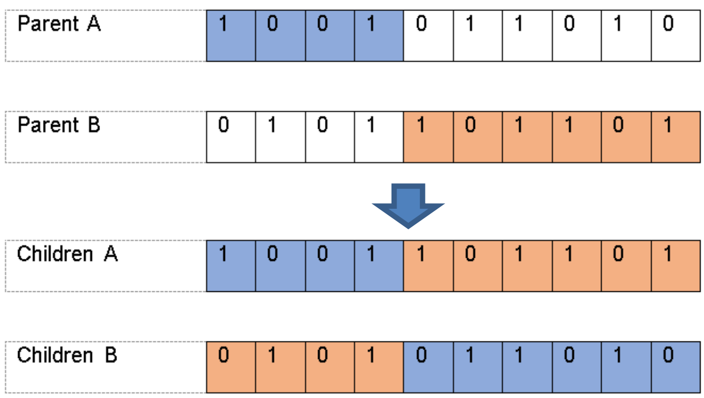

Figure A-6-1: Representation of the crossover operator

The two parents are randomly chosen by using the principle of the *biased roulette wheel*, which makes more probable the choice of parents with low objective functions (but does not exclude a priori the ones with high objective function). In the implementation the inverse of the objective function has been used, as shown in eq. A.1 and A.2:

$$\psi_i = \frac{\frac{1}{(f_{b_i})}}{\sum_{j=1}^{N} \frac{1}{(f_{b_j})}} \tag{A.1}$$

where *N* is the number of chromosomes and thus of fitness functions f_{b_i}, hence

$$\sum_{i=1}^{N} \psi_i = 1 \tag{A.2}$$

Once the parents are chosen, it is randomly imposed the application of the crossover operator (i.e., the parents could be passed to the next iteration even as they are without any changes). Usually, the probability that the crossover is applied is high (in the implemented code the probability that the crossover is applied is 90%).

If the crossover is applied, the cut point (i.e., the point in Figure A-6-1 between the white area and coloured one of the parents) is randomly chosen, and thus the two parts (coloured and white) are exchanged between the two parents, thus creating the offsprings.

The number of elements of the population, after the crossover, is doubled and the choice of the elements to be passed to the next generation is again based on the application of the biased roulette wheel principle.

It is worth to note that the application of the crossover could lead to local minimum, because of the reduction of *diversity* of the chromosomes. This problem is overcome by applying the mutation operator, explained in the next subsection.

Mutation

The mutation is an operator that allows to improve the *diversity* of the population, making possible to avoid (as much as possible) to reduce the solution search close to a local minimum.

The mutation is applied to the single gene according to a specific occurrence probability (fixed at 10% in the implemented code) and is randomly applied to some of the elements chosen randomly, by leading to a change of the status (from 0 to 1 or viceversa). The graphical explanation is shown in Figure A-2.

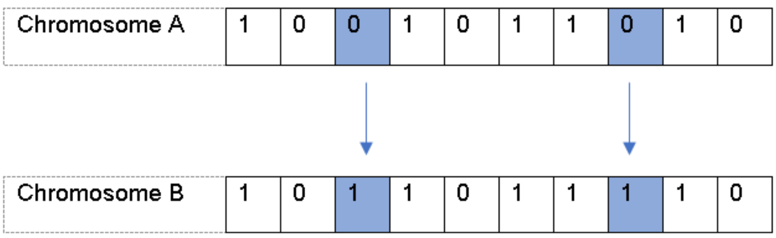

Figure A-2: Representation of Mutation operator

Potential cases

Let us define:

- C_{extr} = extraction for crossover
- p_{cross} = probability of crossover
- M_{extr} = extraction for mutation

- P_{mut} = probability of mutation

Different cases can occur, i.e.,:

1) if C_{extr} > *pCross,* the *Case* counter is updated to 1 that means that the crossover operator is applied, otherwise the *Case* counter is maintained to 0 and the crossover operator is not applied
2) if M_{extr} > P_{mut}, the *Case* counter is updated by adding 1 which means that the mutation operator is also applied.

If the *Case* counter is even, both crossover and mutation are applied (or not applied), whereas if it is odd only one of the two operator is applied, as shown in Table A-6-1.

Table A-6-1: *Case* counter and corresponding operators

Case	Crossover	Mutation
0	not applied	not applied
1	*applied*	not applied
	not applied	*applied*
2	*applied*	*applied*

Elitism

One peculiar aspect of the population-based optimisation method is the *elitism* version. The elitism allows to maintain, along with the generations, the chromosome characterised by the best objective function found so far. This allows to avoid a drawback that can affect the effectiveness of the method and depends on the probabilistic nature of the operations applied.

Stop criteria

Two stop criteria were applied:

- an *adaptive criterion*, which is based on the relative error between the best objective function at the iteration *k* and the one at the iteration *k*-1. If this error is less with respect to a predefined threshold ε, i.e.:

$$\left|\frac{f_{obj}^{(k)} - f_{obj}^{(k-1)}}{f_{obj}^{(k-1)}}\right| < \varepsilon \qquad \text{(A-3)}$$

  for a certain number of iterations, the method stops.

- A last resource stop criterion is used, based on a maximum number of generations processed.

The main advantage provided by the GA implementation in the original code was definitely the reduction of the computation burden: in fact, it allows to run a one-month simulation in about 2 hours.

Appendix B: Implementation of the final version of the code

DAM final code

As a result of the advantage provided by the GA, in terms of computational time reduction, the DAM script was modified in order to allow the simulation of multiple days, as shown in Figure B-6-2.

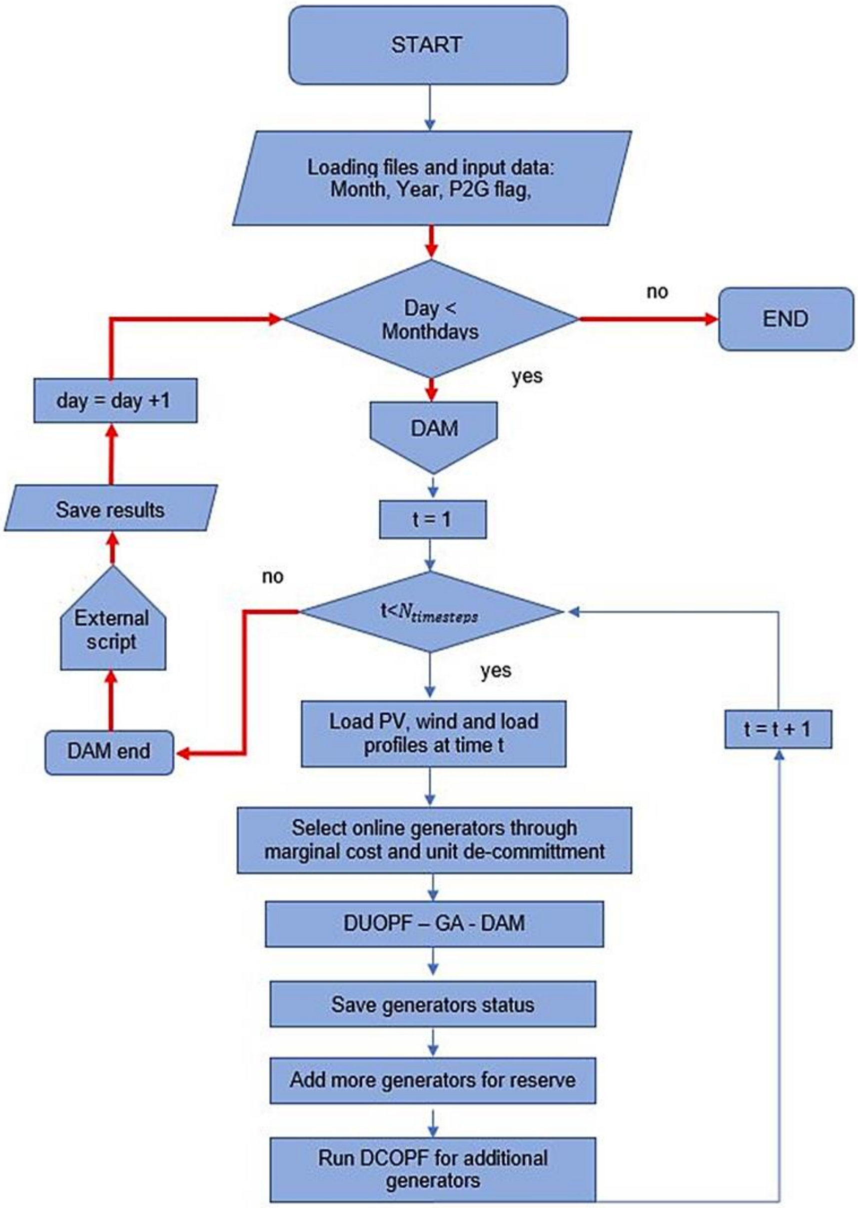

Figure B-6-2: Modified DAM flow chart

With respect to the flow chart reported in [6], the DAM script was converted into a function that is called into a new script, called “DAM_month”, in which the monthly loop is created, as well as the instructions to pass the inputs to the DAM function and to save its daily results. In particular, the most relevant data to set as preliminary step are: month, year and type of year (dry, wet…) selected and *mpc* (representing the grid scenario) as objective of analysis and the power-to-gas flag, that allows to enable or disable the PtG units properly installed into the grid. With such modifications, highlighted in red, it is possible to decide whether to simulate a whole month, a single day or a week.

RTM final code

The same modifications have been applied to the IDM script, in order to simulate up to one month, as shown in Figure B-2.

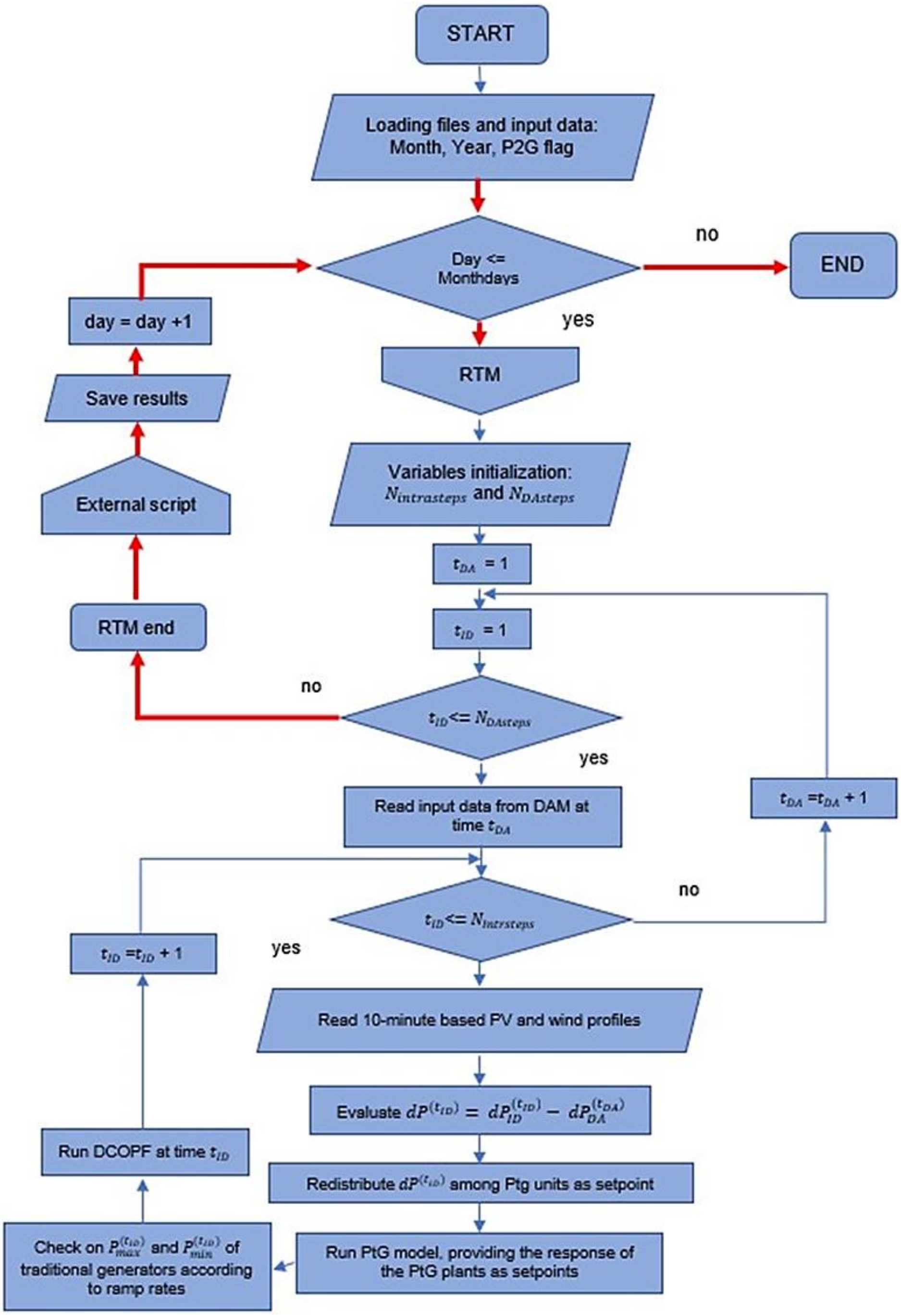

Figure B-2: Modified RTM flow chart

The ID script has been converted to a function as well, in order to be called within the monthly loop at each iteration. The input data are once again month, year and type of year, the PtG flag option and the *mpc,* that allows to select the grid scenario. After each iteration, the daily results are saved to be analysed later. With respect to the previous version, the variation of renewable power produced $dP^{(t_{ID})}$ from the average value has been evaluated between the intra-day value and the renewable DA dispatched output, instead of renewable DAM profiles: that is because of the fact that RES are now constrained to a minimum power output of 15% (average value) of the maximum and it may happen that not all of them are actually or fully dispatched in the day-ahead market.

Scripts for analysis

The results of the simulations are usually divided by month (it depends on the length of the simulated period), thus it is convenient to analyse them by means of a loop that loads them in monthly steps.

In the first part of the code, before the loop starts, all the needed variables required for calculations are initialised. Most of the data existing in the structures saved into simulations results are in the matrix form, hence it is necessary to organise these data in other structures or 3D matrices in order to create monthly archives of valuable information. Specifically, it is possible to select the month and the year of which simulated data will be analysed, the folder from which they will be loaded and other features that distinguish them, such as the network scenario used to get them, and the optional presence of PtG units.

References

[1] ENTSO_E, TYNDP, http://tyndp.entsoe.eu/maps-data/ (on line on 17th July 2018)

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