Power-to-gas as support for the electricity infrastructure

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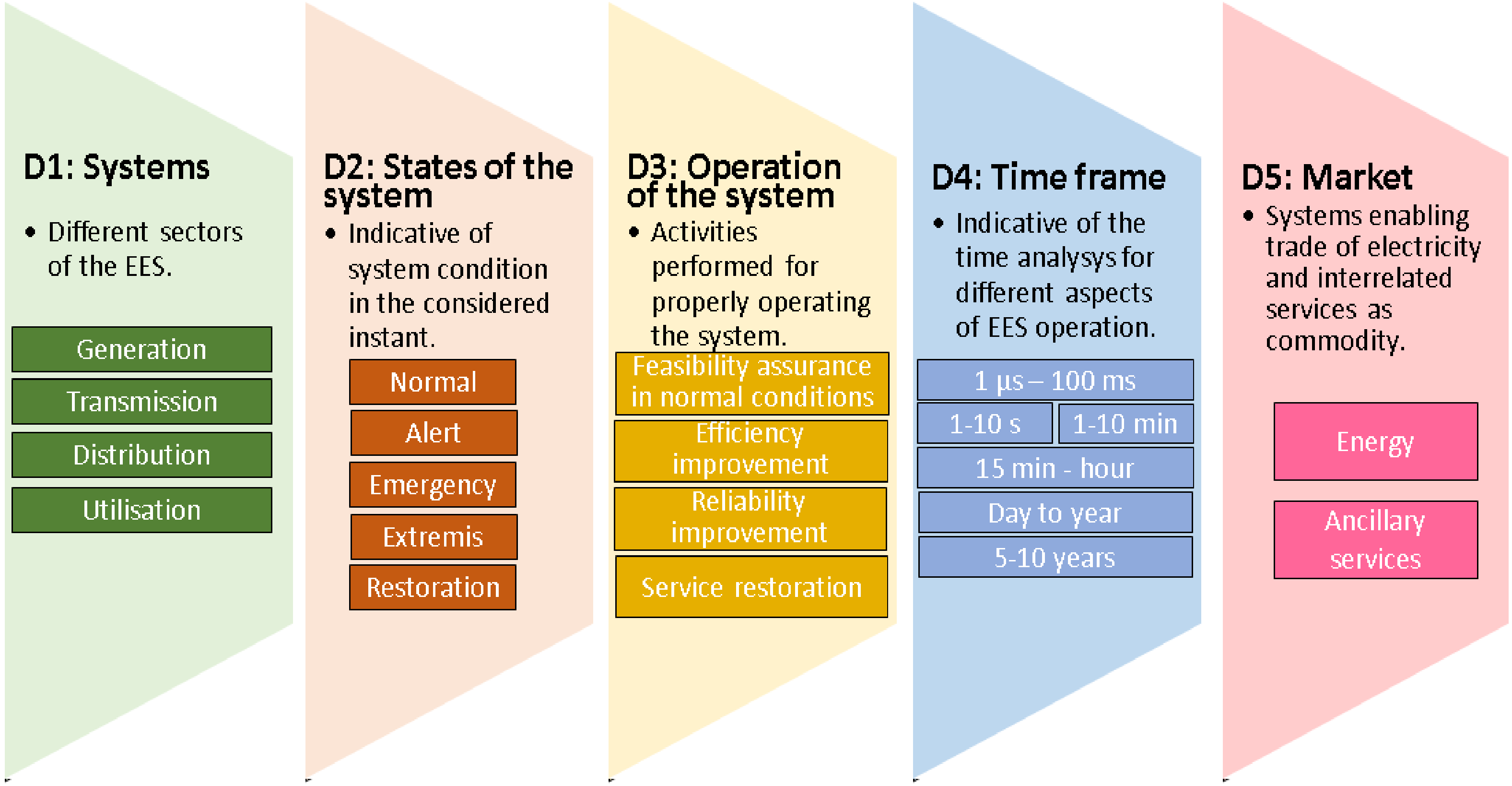
Outline

- Multi-dimensional characterization of electricity systems for PtG integration
- PtG applications to distribution system
- PtG applications to transmission system
- Some concluding remarks

Multi-dimensional characterization of electricity systems for PtG integration

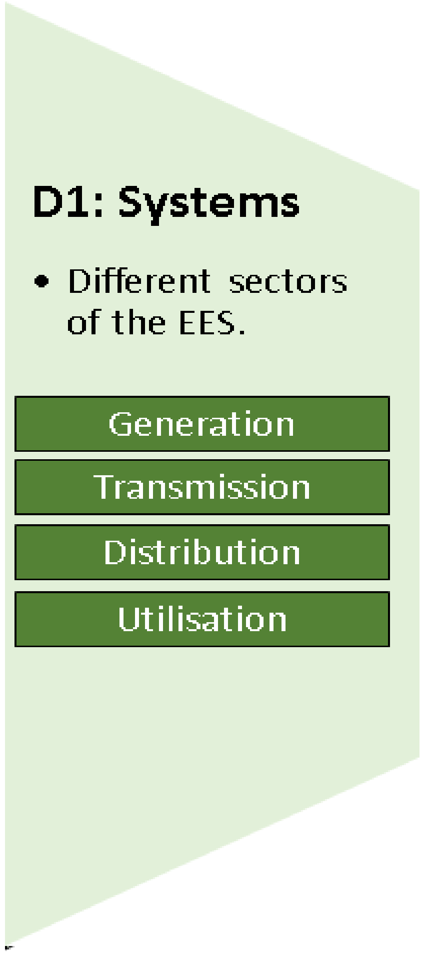
Multi-dimensional characterization the electricity system

- WHAT IS
  - It is a overarching framework for investigating the impact of PtG on electricity system considering all the relevant dimensions
- WHY
  - For creating a common understanding between different backgrounds
  - For recognizing the most promising applications for PtG in electricity system
- HOW
  - The framework considers *five* different dimensions, touching the main aspects of the electricity system



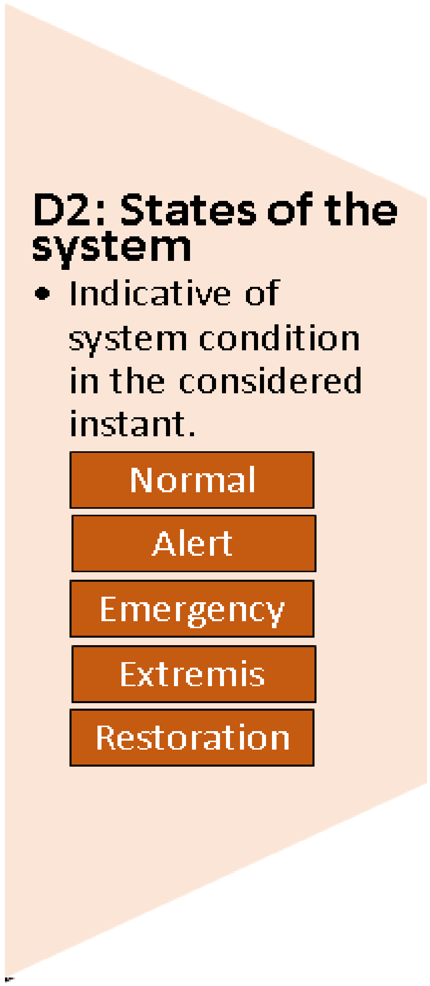
Dimensions D1: Systems

- **The dimension D1:Systems** includes all the different sectors composing the electrical system chain:
  - *Generation*: represents all the activities aiming to convert primary energy (chemical, mechanical, and so on) in electricity.
  - *Transmission*: represents the infrastructure aiming to transfer electricity from the production points toward the load centres.
  - *Distribution*: represents a secondary level infrastructure that allows bringing electricity from the ending point of the transmission network to the customers.
  - *Utilisation*: represents all the customers supplied by the electrical systems.



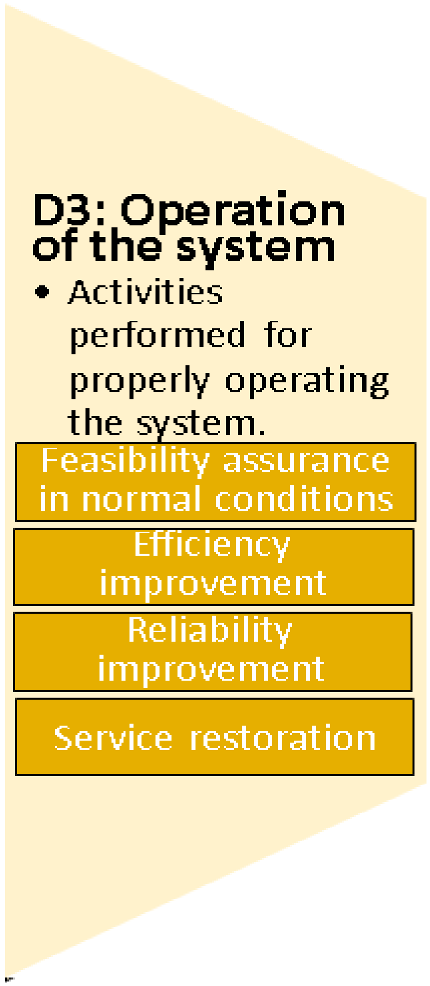
Dimensions D2: States of the system

- **The dimension D2: States of the systems** is indicative of the system condition in the considered time instant
  - *Normal*: it is the typical operation condition of the system, when all the variables lie in the feasible ranges.
  - *Alert*: the system still operated properly, but it is identified a condition that can bring the system to the emergency state.
  - *Emergency*: the system is characterized by some operative variables out of the normal ranges.
  - *Extremis*: condition in which the system is no longer working (e.g., blackout).
  - *Restoration*: condition post-extremis, when the system is managed for bringing it again back to the normal state.



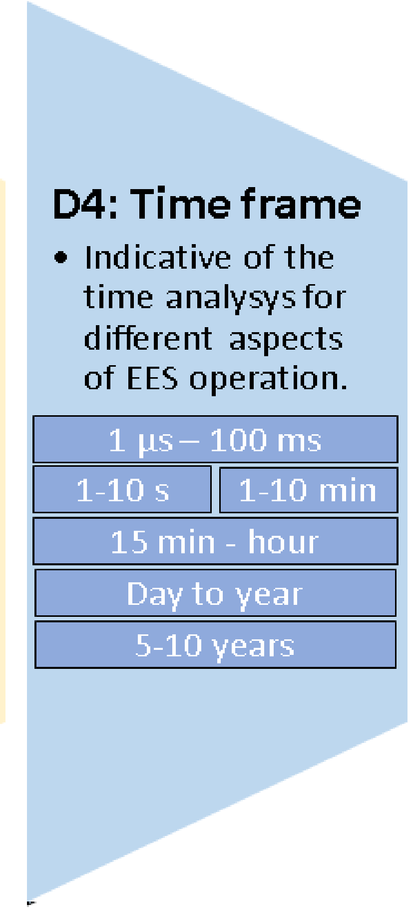
Dimensions D3: Operation of the system

- **The dimension D3: Operation of the systems** is indicative of the activities carried out for properly operating the system.
  - *Feasibility assurance in normal condition*: it represents all the activities that guarantees the compliance of the system variables to the operation ranges (e.g., voltage and frequency regulation regulation)
  - *Efficiency improvement*: set of actions put in place to operate the more efficiently (e.g., by reducing the losses)
  - *Reliability improvement*: set of actions carried out for ensuring a reliable system (e.g., maintenance plan).
  - *Service restoration*: it represents all the activities performed for restoring the service in case of fault (e.g., reconfiguration plan).



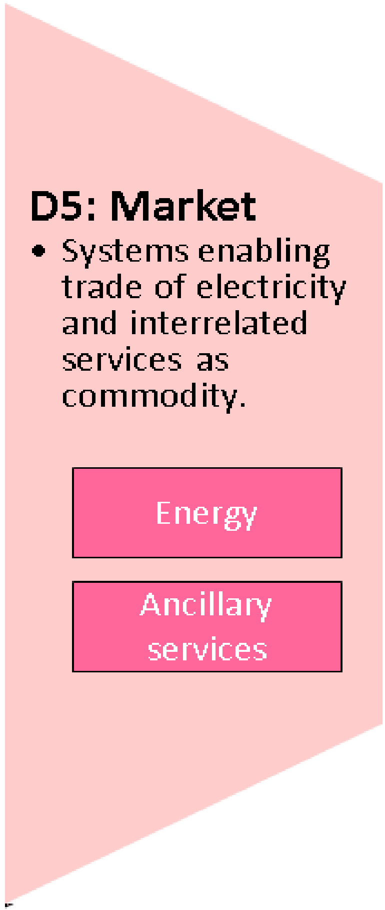
Dimensions D4: Time frame

- **The dimension D4: Time frame** is indicative of the analysis for different aspects of the electricity system
- The range is really wide:
  - **≈ 1 μs–100 ms**: requested for *electromagnetic* transients
  - **≈ 1–10** s: requested for *electromechanical* transients, when the aim is the study of the rotational speed of the generators.
  - **≈ 1–10 minutes**: requested to characterise very precisely the behaviour of the non-dispatchable units and to study primary frequency regulation support
  - **15 minutes to hours**: requested to characterise most of the loads and the generation units for quasi-steady state studies, and the secondary and tertiary frequency regulation.
  - **From day to year**: requested for studying the optimal operation of the system (e. g., dispatching and losses minimisation).
  - **Five to ten years** (or more): requested for planning purposes.



Dimensions D5: Market

- **The dimension D5: Market** is indicative of the system trade of electricity and interralated services as commodity:
  - *Energy market*: where operators sell and buy electricity aiming to satify the load requests
  - *Ancillary services* market: where the system operator buys energy and capacity for guaranteeing the safe operation of the system.



Synoptic view and classification of the scientific paper about PtG

- The synoptic view of the dimensions shown as table useful to *classify the scientific papers in literature*, but also to *highlight the feature of any applications*

Application	Description of the application	D1 System Structure				D2 State of the system					D3 Operation of the system				D4 Time frame						D5 Market	
		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

- ***Published scientific** so far consider:*
  - *mostly PtG connected to the **transmission system -------------------> 1.2***
  - *electricity system is in **normal conditions --------------------------------> 2.1***
  - ***Feasibility assurance** in normal conditions (e.g., load balancing) **-> 3.1***
  - *as typical time frame the range **1 day to year**; **---------------------------> 4.5***
  - *often the **day-ahead market --> 5.1***

Classifications of the presented applications

- **Application 1: Use of PtG plants to solve issues affecting the distribution system due to very large RES penetration**
  - D1.3 Distribution system: the system under analysis is the distribution system. Different samples of network are required to properly represent the different network conditions.
  - D2.3 Alert or D2.4 Emergency: due to the simulated large amount of RES installed, the system is not operated at normal conditions. The constraints can be either satisfied (D2.3 Alert) or not (D2.4 Emergency).
  - D3.1 Feasibility assurance of the normal operation conditions: the installation of PtG aims to restablish the normal operation conditions
  - D4.5 One day to year: the application aims to cover different seasons for understanding the impact of PtG on the network with different level of RES penetration
  - D5.2 Ancillary service market: the service proposed could be provided as ancillary service (NB: the market layer has not been simulated)

Classifications of the presented applications

- **Application 2: Use of PtG plants to increase the amount of RES dispatched at EU level, by handling the RES variability and by avoiding as much as possible the change in the dispatch program of traditional generators**
  - D1.2 Transmission system: the system under analysis is the European transmission system. Proper models of the entire system is required
  - D2.1 Normal conditions: the system is supposed to be in normal conditions both before and after the PtG installation
  - D3.1 Feasibility assurance of the normal operation conditions: the installation of PtG do not have to affect the normal operation of the grid
  - D4.5 One day to year: the application aims to cover different seasons for understanding the impact of PtG on the system with different RES penetration scenarios
  - D5.2 Ancillary service market: the service proposed could be provided as ancillary service (i.e., balancing service, NB: the market layer has been simulated through Optimal Power Flow at constant load).

Synoptic view of the two applications

Application	D1 System Structure				D2 State of the system					D3 Operation of the system				D4 Time frame						D5 Market	
	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
Application 1			X			X*	X*			X								X			X
Application 2		X			X					X								X			X

Some analysis undertaken

- **Improvement of the *operation* of the network, by solving issues due to the high RES penetration**
  - Congestions
  - Voltage issues
  - Reverse power flow
- **Investigation of the role of PtG as alternative to network investments**
- **Impact of PtG on the electricity cost**

Reference networks for the analysis

- **2 study-cases for PtG integration**
  - European Transmission Network
    - 256 nodes
    - Load and Renewable Energy Sources (RES) generation projection until 2040
    - Proper emulation of 10-min variability of RES
  - Distribution systems
    - Rural network, composed of 102 nodes, including photovoltaic (PV) generation based on the Troia’s demo site location
    - Semi-urban network, composed of 202 nodes, including photovoltaic (PV) generation based on the Solothurn’s demo site location

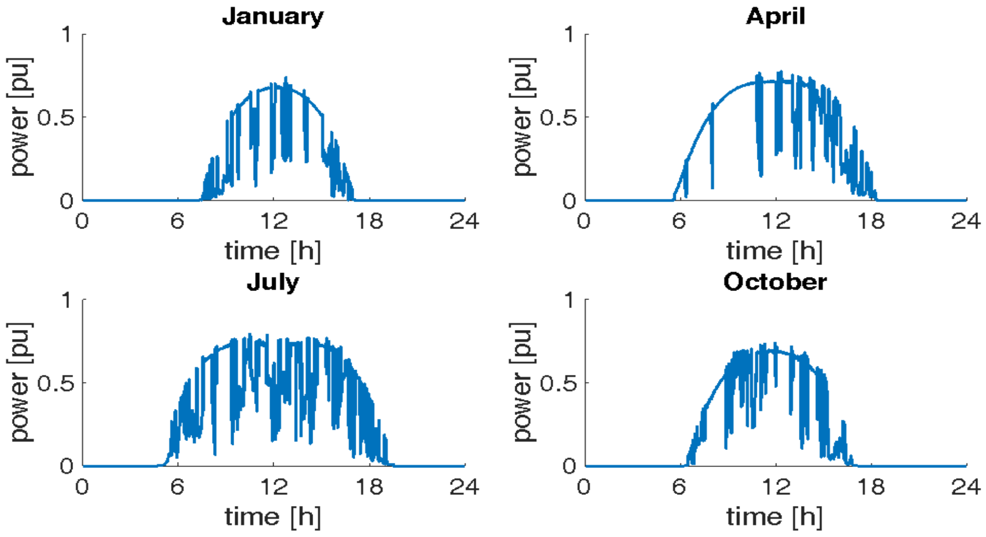
Distribution system

Distribution system: issues from high RES penetration

- **Reverse power flow**
  - issue for both transmission and the distribution system operators
  - the interconnection between distribution system and transmission system equivalent to a non-controllable active node
  - not proper protection schemes at distribution level
- **Overcurrent**: the large share of RES can create overcurrents along the feeders. These overcurrents can affect only a portion of the network (e.g., the last portion) or the entire network, depending on the **level of load** and distributed generation, together with the **geographical position** of the PV plants.
- **Overvoltages**: this problem is characteristic especially of rural networks, composed of long feeders (also up to 10 km), and characterised of high R/X ratio (due to the relatively small sections)

Rural network

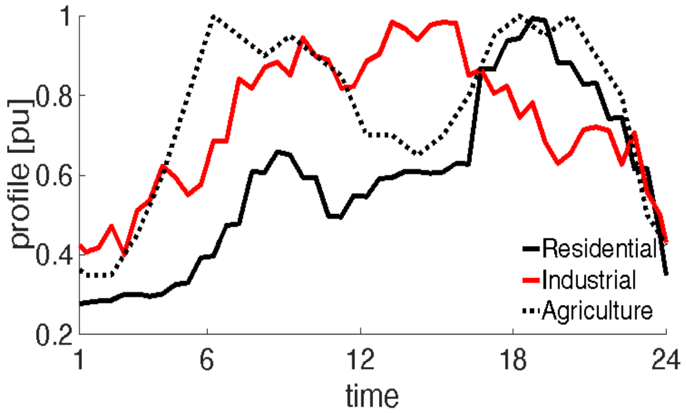
- Representative of a rural network in the south of Italy -> linked with the demo site of Troia

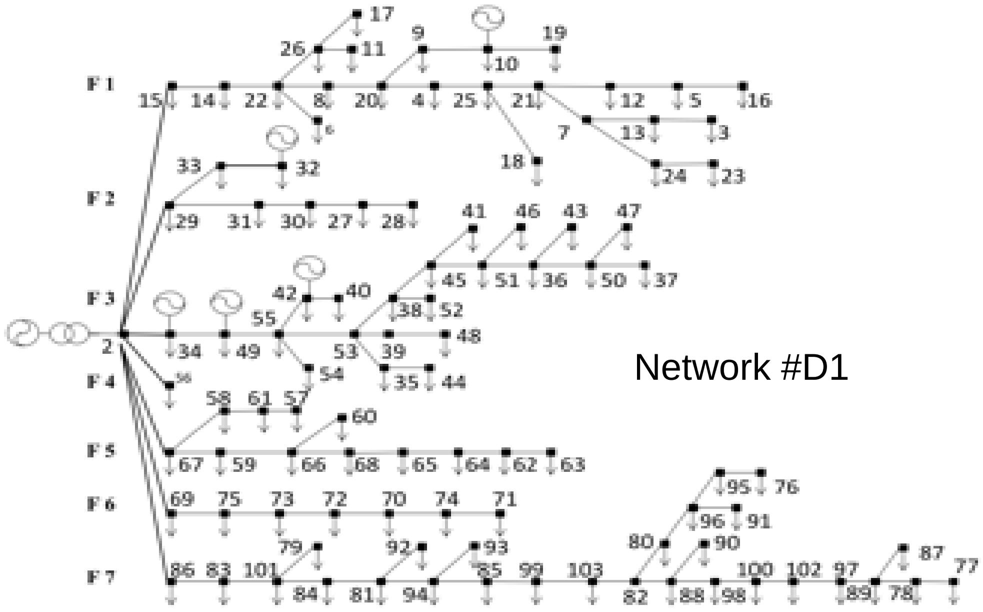


PV daily profiles in four different seasons

Feeder	Nodes	#Residential	#Industrial	#Agricultural	#PV
F1	3 – 27	7	2	16	1
F2	28 – 33	0	2	6	1
F3	34 – 55	13	3	9	3
F4	56	1	0	0	0
F5	57 – 69	5	3	12	0
F6	70 – 76	1	1	7	0
F7	79 – 103	13	3	17	0

Load profiles



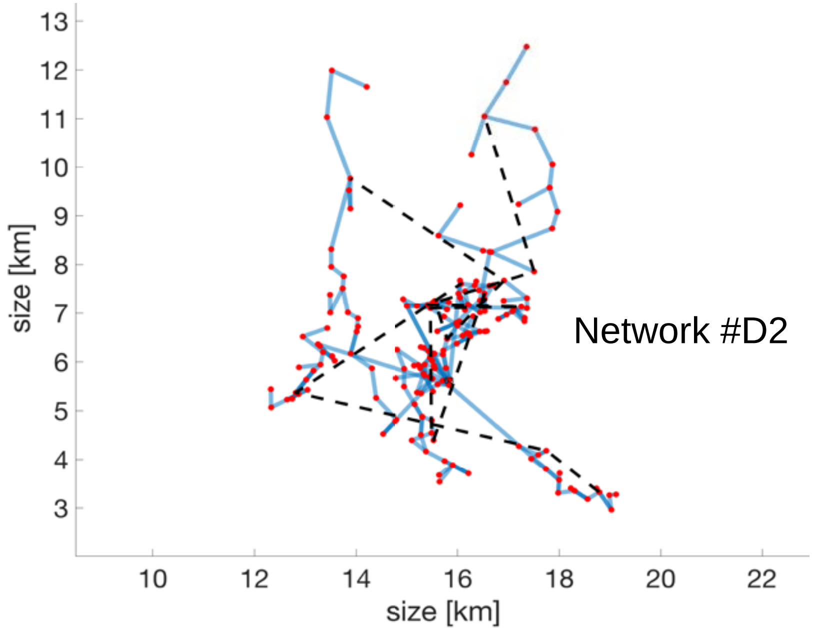


Network #D1

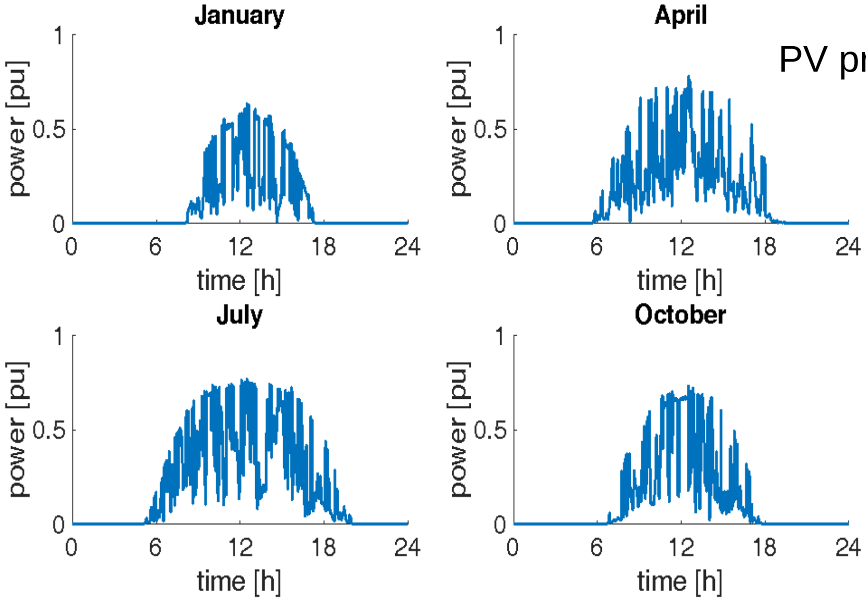
Semi-urban network

- Representative of a EU semi-urban network -> linked with the demo site of Solothurn

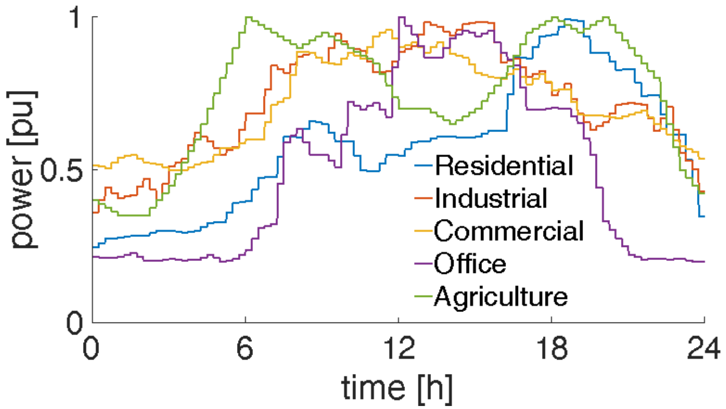
Line length L [km]	% residential	% industrial	% commercial	% offices	% agriculture
$L \leq 0.15$	80	0	10	10	0
$0.15 < L \leq 0.3$	70	0	15	15	0
$0.3 < L \leq 0.5$	65	5	15	15	0
$0.5 < L \leq 0.8$	25	5	45	20	5
$0.8 < L \leq 1$	10	50	25	5	10
$1 < L \leq 3.5$	20	10	5	5	60



Network #D2



PV profiles



Load profiles

Creation of the proper case study: PV placement in the network (1)

- The creation of the “network issues” (reverse power flow, overcurrents and overvoltages) needs proper PV placement in the network
- To cover a wider spectrum of cases (with different PV locations), two main methodologies have been adopted::
  - **Method 1**: based on *line length*
  - **Method 2**: Based on *loss allocation factors*, without constraints verified (*Method 2a*) and with constraints verified (*Method 2b*) -> the two methods allows to create scenarios according to the D2.2 Alert or D2.3 Emergency
  - In general, for both networks:
    - Possibility to isolate reverse power flow (network constraints verified)
    - Mixed problems (i.e., reverse power flow, overcurrents and/orovervoltages) with high PV penetration

Creation of the proper case study: PV placement in the network (2)

Method PV placement	Length [km]	PV penetration	Reverse PF	Overcurrent	Overvoltage
Method 1	$0<L \leq 0.9$	50%	X	-	-
		60 %	X	-	-
		70 %	X	X	-
		80 %	X	X	-
	$2 \leq L \leq 3$	50 %	X	-	-
		60 %	X	-	-
		70 %	X	-	X
		80 %	X	-	X
Method 2a	-	50 %	X	X	-
		60 %	X	X	-
		70 %	X	X	X
		80 %	X	X	X
Method 2b	-	50 %	X		
		60 %	X		
		70 %	X		
		80 %	X		

- **Possibility to isolate reverse power flow** (network constraints verified) -> D2.2 Alert
- **Mixed problems** with high PV penetration -> D2.3 Emergency

Example of PV installation for the rural network, based on line length

Length [km]	Feeder	PV Installed Power [MW]				
		40%	50%	60%	70%	80%
$0<L \leq 0.9$	F1	3.42	3.61	5.218	5.963	6.708
	F2	1.06	1.85	1.618	1.850	2.081
	F3	0.65	0.80	1	1.146	1.290
	F4	0.66	0.80	1	1.149	1.293
	F5	1.79	2.18	2.730	3.126	3.510
	F6	0.54	0.66	0.835	0.9547	1.074
	F7	6.47	7.87	9.8459	11.252	12.659
$2 \leq L \leq 3$	F1	2.95	3.59	4.498	5.140	5.783
	F2	2.59	3.15	3.947	4.511	5.075
	F3	3.59	4.37	5.474	6.256	7.038
	F4	0	0	0	0	0
	F5	0	0	0	0	0
	F6	1.31	1.549	1.990	2.280	2.565
	F7	4.16	5.07	6.341	7.247	5.800

- Due to the fact that the PV is distributed according to the structure of the netwrok, some feeders have much more PV installed than other
- F7, for lenght up to 900 m
- The couple F3/F7 by considering lines with length between 2 and 3 km

Example of PV installation for the rural network, based on loss allocation

Method PV placement	Length [km]	Feeder	PV Installed Power [MW]				
			40%	50%	60%	70%	80%
Method 2a		F1	14.62	16.53	20.67	23.62	26.57
		F2	0	0	0	0	0
		F3	0	0	0	0	0
		F4	0	0	0	0	0
		F5	0	0	0	0	0
		F6	0	0	0	0	0
		F7	0	0	0	0	0
Method 2b		F1	5.25	6.33	6.33	7.63	7.63
		F2	3.45	2.11	2.11	2.26	2.66
		F3	5.56	7.65	8.05	8.20	8.20
		F4	0	0.15	0.15	0.20	0.20
		F5	0	0	0	0	5.55
		F6	0	0	0	1.30	1.95
		F7	0	1.95	5.15	5.80	5.80

- On one hand, If no constraint check is made, the algorithm suggests to installed all the PV in F1
- On the other hand, if the constraint check is introduced a more hoogeneous distribution of PV plants is found

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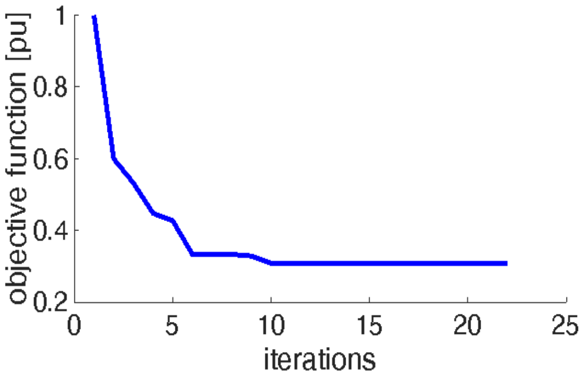
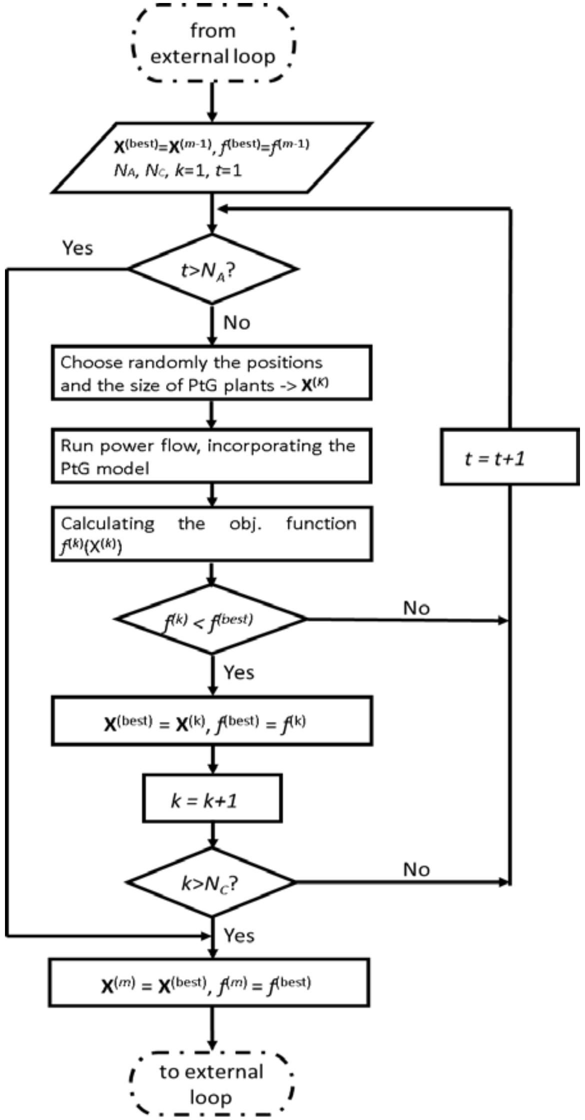
Siting and sizing of PtG plants: Simulated Annealing and objective functions

- Once proper case studies are created, then the (pseudo-optimal) installation sites and plant sizes are calculated
- One possible approach (able to handling with the local minima of the problem) is the use of meta-heuristics, such as the Simulated Annealing
- The Simulated Annealing (SA) algorithm is an iterative meta-heuristic method composed of an external loop and an internal loop and it mimics the annealing of the metal
- The external loop is functional to change the input parameters provided to the internal loop, which is the one calculating the objective function value and comparing it with the old one
- The objective functions introduced consider:
  - Only presence of reverse power flow
  - Co-existence of both reverse power flow and overcurrent
  - Co-existence of both reverse power flow and overvoltages





How to check the results

- The rationale behind the installation of PtG in distribution system is composed of the following points:
  - **Improvement the network performance** during the period with **highest PV production** (e.g, in July)
  - The installation should **not create problems during the period with lower PV production** (e.g., January)
  - The “**load factor**” of the plants should be **high enough** to justify the installation of the plant (NB: a deeper evaluation considering CAPEX and OPEX of the plant is required, but the in presence of low load factor for sure the application should be discarded)

Rural network results

Chosen results for the rural network- overview

Length [km]	PV penet	Rev. PF pre [min]	Rev. PF post [min]	Overcurr. Pre [min]	Overcurr. Post [min]	Overvolt. Pre [min]	Overvolt. Post [min]
$0<L \leq 0.9$	40 %	113	6	-	-	-	-
	50 %	211	4	-	-	-	-
	60 %	366	23	-	-	-	-
	70 %	454	152	360	0	-	-
	80 %	506	256	578	7	-	-
$2 \leq L \leq 3$	40 %	144	9	-	-	-	-
	50 %	232	8	-	-	-	-
	60 %	370	28	-	-	-	-
	70 %	429	182	-	-	463	0
	80 %	488	291	-	-	1297	9

- Very good performance, with almost the complete resolution of the reverse power flow at lower penetration

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Chosen results for the rural network - overview

Length [km]	PV penet	Rev. PF pre [min]	Rev. PF post [min]	Overcurr. Pre [min]	Overcurr. Post [min]	Overvolt. Pre [min]	Overvolt. Post [min]
$0<L \leq 0.9$	40 %	113	6	-	-	-	-
	50 %	211	4	-	-	-	-
	60 %	366	23	-	-	-	-
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	50 %	232	8	-	-	-	-
	60 %	370	28	-	-	-	-
	70 %	429	182	-	-	463	0
	80 %	488	291	-	-	1297	9

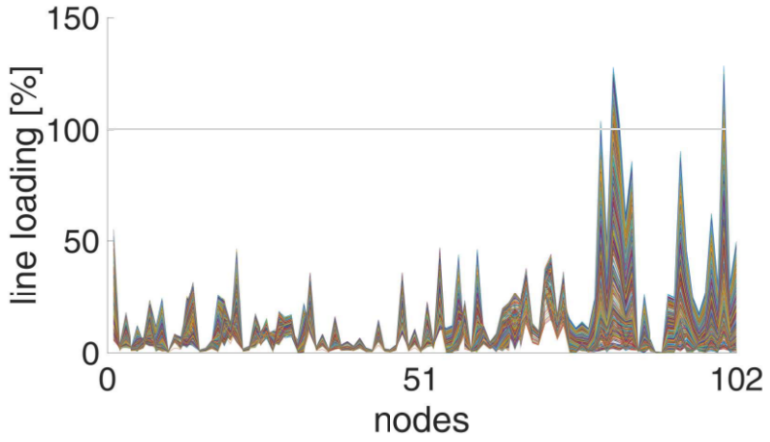
Deeper analysis of this case

- Very good performance, with almost the complete resolution of the reverse power flow at lower penetration
- Not bad performance with higher penetrations, at which the PtG alleviates and the network problems (e.g., overvoltages and over currents)

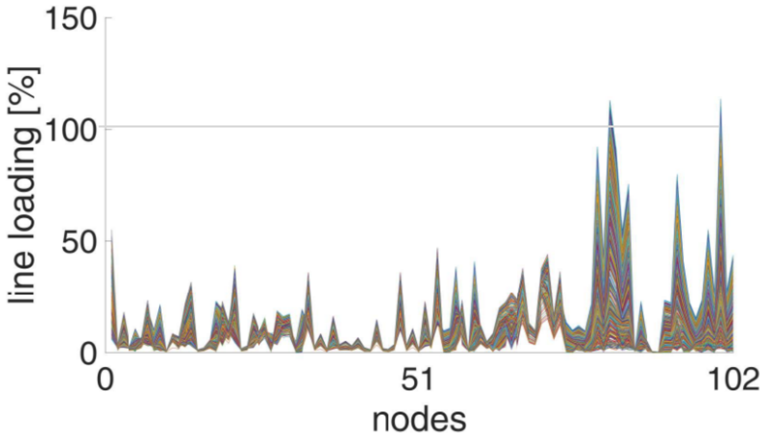
Analysis of the residual overcurrents

Length [km]	PV penet	Overloaded branches	Magnitude	Persistence [min]
0< *L* ≤0.9	80 %	82	7.5%	2
		83	6.5%	3
		100	6.7%	2

- Even if still some overcurrents exist, they are very limited and does not really affect the normal operation of the network.



(c) 0< *L* ≤0.9 km, 80% PV penetration, before the installation



(d) 0< *L* ≤0.9 km, 80% PV penetration, after the installation

Results for the rural network – losses and reverse power flow

Length [km]	PV penet.	Network losses [MWh] pre-installation	Network losses [MWh] post-installation	Network losses [%] pre-installation	Network losses [%] post installation
0<L ≤0.9	40 %	3.08	3.02	2.17	1.85
	50 %	3.53	3.88	2.70	2.06
	60 %	4.23	3.55	4.08	1.90
	70 %	5.06	3.50	6.41	2.14
	80 %	5.88	3.84	9.88	2.63
2 ≤ L ≤ 3	40 %	3.06	2.75	2.23	1.74
	50 %	3.71	4.03	2.88	2.03
	60 %	4.88	4.69	4.78	2.69
	70 %	5.99	5.15	7.22	3.42
	80 %	7.31	5.59	11.51	4.27

- Reduction of the percentage losses in all the cases
- Reduction in some cases also of the losses value in absolute terms (reduction of the losses when PtG absorbs the PV production overcoming the additional losses for the night operation of the plant)

- Strong reduction of the reverse PF (at least 67%)

Length [km]	PV penet	Rev. PF pre [MWh]	Rev. PF post [MWh]	Reduction [%]
0< L ≤0.9	40 %	1.02	0.051	-95.00
	50 %	5.78	0.086	-98.50
	60 %	20.38	0.39	-98.07
	70 %	36.25	3.06	-91.55
	80 %	50.96	10.39	-79.60
2 ≤ L ≤ 3	40 %	1.79	0.076	-95.74
	50 %	5.48	0.11	-97.94
	60 %	19.68	0.96	-95.14
	70 %	32.38	4.94	-84.76
	80 %	46.43	15.14	-67.40

Check of the load factors for the rural network

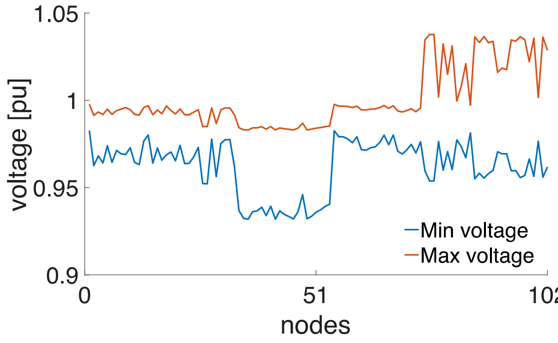
- The check of the load factor is required for understanding if the plants capacity is well exploited or not
- The load factors of the PtG plants installed are quite **high** in all the cases (also for the plants with the minimum load factors)

Method PV Placement	PV penet	Node Min Load factor	Load factor [%]	Node Max Load factor	Load factor [%]
$0<L \leq 0.9$	40 %	82	70.37	-	-
	50 %	21	68.89	27	81.66
	60 %	93	80.41	100	88.04
	70 %	13	55.07	85	86.59
	80 %	21	64.71	83	87.49
$2 \leq L \leq 3$	40 %	87	68.67[1]	-	-
	50 %	85	62.98	81	79.23
	60 %	44	63.38	100	79.69
	70 %	21	58.13	97	87.97
	80 %	48	73.31	97	89.68

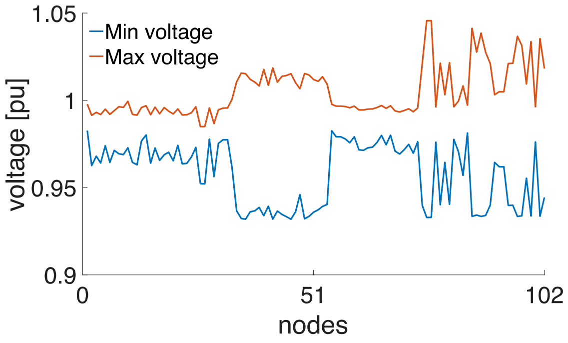
[1]Particular case, with only 1 PtG installed

Check of the impact on the network of the installed PtG with low PV penetration

Length [km]	PV penet.	Network losses [MWh]		Network losses [%]	
		pre-installation	post-installation	pre-installation	post installation
0<L ≤0.9	40 %	3.43	3.30	1.93	1.67
	50 %	3.59	4.06	2.20	1.90
	60 %	3.95	3.81	2.45	1.73
	70 %	4.44	3.78	3.00	1.81
	80 %	4.87	4.08	3.56	2.05
2 ≤ L ≤ 3	40 %	3.27	3.28	1.84	1.70
	50 %	3.72	4.15	2.11	1.82
	60 %	4.32	4.58	2.69	2.15
	70 %	4.90	4.67	3.26	2.35
	80 %	5.59	5.01	4.02	2.68



(a) 0< L ≤0.9 km, 40% PV penetration, January



(b) 2< L ≤3 km, 40% PV penetrarion Januaryy

- The network performance are still good
- The problem that can be appears can be presence of nodal voltages lower than the minimum feasible value (i.e., 0.9 pu)
- However, the graphs show for two particular cases that the voltage values are within the acceptable values

Semi-urban network results

Chosen results for the semi-urban network - overview

Length [km]	PV penet.	Rev. PF pre [min]	Rev. PF post [min]	Overcurr. Pre [min]	Overcurr. Post [min]	Overvolt. Pre [min]	Overvolt. Post [min]
0<L ≤0.45	30%	16	1	-	-	-	-
	40%	161	27	-	-	-	-
	50 %	278	32	-	-	-	-
	60 %	362	42	-	-	-	-
	70 %	411	159	2	1	-	-
	80 %	459	203	426	9	-	-
0.5≤ L ≤ 3	30 %	11	0	4	0	-	-
	40 %	161	10	1287	80	17	0
	50 %	268	56	2972	389	909	0
	60 %	354	150	4954	667	1810	0

- Very good performance, with the complete resolution of the reverse power flow at lower penetration
- Good performance with higher penetrations, at which the PtG alleviates and the network problems (e.g., overvoltages and over currents)

Results for the semiurban network – losses and reverse power flow

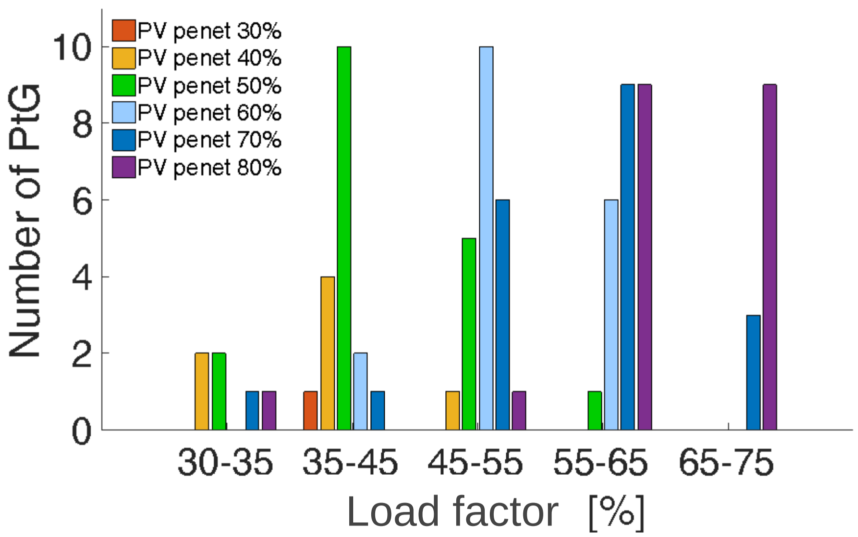
Length [km]	PV penet.	Network losses [MWh]		Network losses [%]	
		pre-installation	post-installation	pre-installation	post -installation
0<*L* ≤0.45	30%	6.14	6.22	0.80	0.80
	40%	5.74	6.31	0.87	0.84
	50 %	5.68	7.14	1.04	0.79
	60 %	6.06	7.00	1.40	0.82
	70 %	6.83	6.97	2.11	0.91
	80 %	7.98	7.46	3.71	1.10
0.5 ≤ *L* ≤ 3	30 %	7.86	7.61	1.03	0.97
	40 %	9.34	8.59	1.43	1.02
	50 %	11.80	10.35	2.17	1.18
	60 %	15.19	11.36	3.51	1.36

- Reduction of the percentage losses in all the cases
- In absolute terms the losses decrease after the installation of PtG only when the PV is installed on longer lines

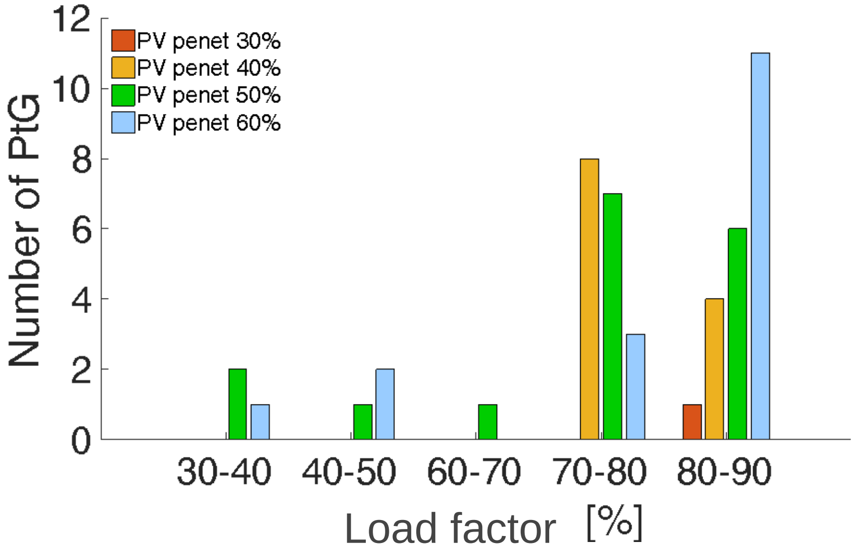
- Strong reduction of the reverse PF (at least 72%)

Length [km]	PV penet	Rev. PF pre [MWh]	Rev. PF post [MWh]	Reduction [%]
0<*L* ≤ 0.450	30 %	0.18	0.002	-98.68
	40 %	27.09	3.20	-88.17
	50 %	81.67	6.49	-92.05
	60 %	152.51	13.10	-91.40
	70 %	231.66	41.97	-81,88
	80 %	316.84	88.61	-72.03
0.5 ≤ *L* ≤ 3	30 %	0.11	0	-100
	40 %	25.82	0.74	-97.13
	50 %	76.80	4.42	-94.23
	60 %	144.40	26.19	-81.85

Check of the load factors



case 0 < L ≤ 0.45 km



case 2 ≤ L ≤ 3 km

- The number of PtG is higher than the ones used in the rural network, and their sizes are larger
- So, the load factor is lower, but at minimum is **30%**
- The distributions show that the higher is the PV penetration, the higher is the load factor

Summary of the results

PtG benefit in the distribution system - 1

- The network problems (i.e., reverse power flow, overcurrents and overvoltages) have been significantly reduced and, in some cases, also completely eliminated
- By considering the **rural network**, a number of PtG plants (from **1 to 5** according to the PV penetration) have been optimally installed, with the aim to reduce the amplitude and the persistence of the network issues
- In the case 0< $L \leq 0.9$ km sees a reduction of the reverse power flow energy falling in the range **79-95**%, whereas in the case $2 \leq L \leq 3$ km the reduction lies in the range **67-95** %.
- In all cases, the installation of PtG is also able to alleviate the constraints problems, by reaching their complete elimination for the lower PV penetrations.

PtG benefit the distribution system - 2

- For the **semi-urban network**, the number and the sizes of the PtG plants are higher (up to 20) than the ones used for the rural network, due to the higher number of nodes and higher load.
- Also in this case, the location and the size of PtG plants have been optimised to reduce the amplitude and the persistence of the network problems.
- The results obtained are really good, with a reduction of the reverse power flow energy falling in the range **72-98**%, with better performances for lower PV penetration.
- Furthermore, in all the cases the installation of PtG plants has reduced the percentage losses of the network

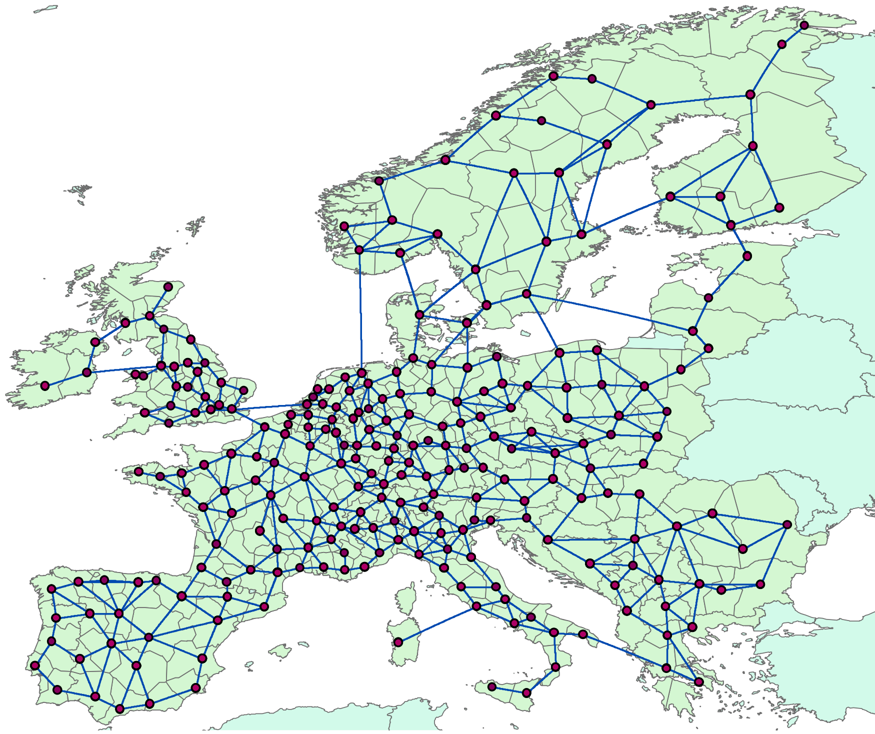
PtG benefit in the distribution system - 3

- The load factor of the plants provides information on how much a PtG plant is used: these values are particularly high (even around 90% for some cases of the rural network) and their variation depends on the PV penetration value, on the positioning of the PtG and on the size.
- This suggest that the installation of PtG plants at the level of distribution system has to be made by considering the **local characteristics** of the network
- In conclusion, it can be said that the addition of PtG systems in a distribution network can stabilize the network even for very high (even extreme) penetrations, thus increasing the ability of a network to host higher penetration of intermittent generation.

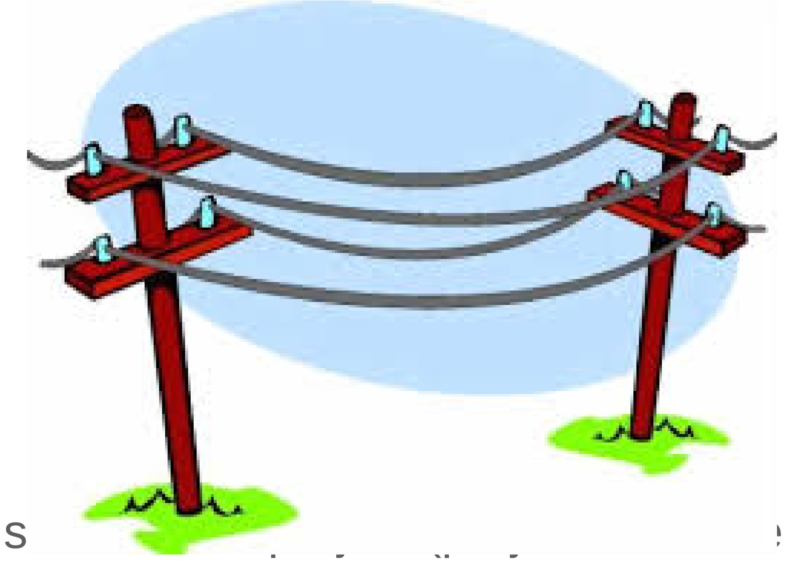
Transmission system

Transmission system model

- The detailed study of the integration of PtG into the transmission network needs the following features:
  - **Proper description of the transmission network**: this means the implementation of realistic transmission system, in terms of physical parameters (e.g., resistance, reactance, length, line thermal limits and so on)
  - **Geographical coverage**: in the usual load flow analysis, the geographical coverage is not so much important. However, by handling with a new technology which aims to support the integration of RES in Europe, the geographical information is necessary
  - **Proper values of generation and loads**: the mix of generation and loads regarding the next decades (e.g., 2030 and 2040)
- The model of the transmission network used is composed of **256 nodes**
- Every node corresponds to a ***cluster***, whose extension is based on the population and gross domestic product



Evaluation of the impact of PtG plants – Research questions



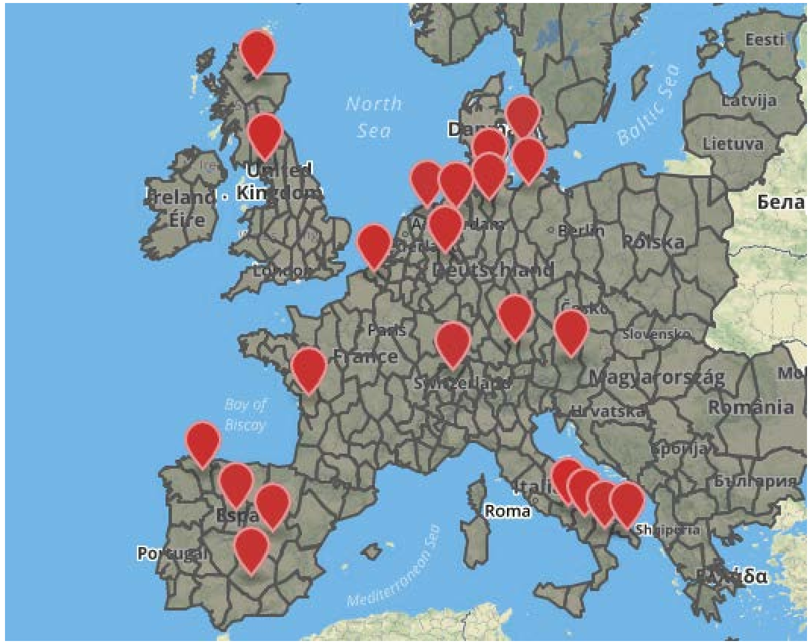
- Research questions:
  - How many plants will be acceptable?
  - Where will they be located?
  - Which will the future scenario considered?
- Answers:
  - The capacity of PtG was defined by considering CAPEX defined s years 2040 and 2050) and a portion of the forecasted investment on the European electricity system up to 2040
  - The location of PtG plants is in turn related to the availability of CO_2 sources *and* RES curtailment
  - The future scenarios have been derived from the Ten-Year Network Development Plan, developed by ENTSO-E and ENTSO-G

Evaluation of the impact of PtG plants – Research inputs

- **Total investments related network infrastructure** up to 2040: **~60 B€$_{2018}$**
- As hypothesis around 20% of the total investments has been **diverted towards PtG**: **~16 B€$_{2018}$**
- By considering a forecast CAPEX lying between 65-95 M€$_{2018}$ referred to 100MW plant, the total amount of PtG installed in Europe lies between 17 and 24 GW.
- Among all the scenarios, two in particular have been considered in the analysis because considers a percentage of Synthetic Natural Gas in their energy mix:
  - **Global Climate Action (GCA) 2040**: 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.
  - **Distributed Generation (DG) 2040**: consumers as the centre of the entire energy strategy. More decentralised technology is taken into account

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

Evaluation of the impact of PtG plants – Location and size



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

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

- The location and sizes of the PtG have been obtained by considering:
  - The availability of CO_2
  - The presence of RES production
  - Presence of RES curtailment

Evaluation of the impact of PtG plants – Dispatch of RES

- The amount of RES dispatched is increasing with the use of PtG, in all the scenarios, between **7% and 16%**

Case 17 GW, Scenario GCA 2040

	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

Case 17 GW, Scenario DG 2040

	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

Case 24 GW, Scenario GCA 2040

	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

Case 24 GW, Scenario DG 2040

	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

Synthetic Natural Gas production

- Annual electricity absorbed by PtG plants and equivalent working hours:

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

- Annual SNG production
  - The produced SNG is **higher than the expected prodution** from PtG in the scenario **DG 2040** .
  - Regarding the scenario **GCA 2040** , the installation of **24 GW allows to overcome the expected production** from PtG for that scenario.

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

Average price of the electricity

- From the system point of view, the installation of PtG is beneficial
- In fact, the average electricity cost reduces with the increase of the share of 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%)

- This is due to the fact that a higher value of RES is dispatched, which leads to a reduction of the overall system cost

Conclusions

- A network with additional flexibility is required to allow the dispatch of a larger share of RES.
- The results show that the PtG technology improves the RES dispatch by simply adding new facilities. The improvement lies in the range between 7% 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

Back up slides

Objective functions

- Presence of only reverse power flow:

$$f_k(\mathbf{X}) = \frac{RPF_k}{RPF_0} \cdot \left(1 + \sum_{j\in\mathbf{J}} \rho_V \left(\frac{V_j^{(max)} - V_j^{(worst)}}{V_j^{(max)}}\right)^2 + \sum_{j\in\mathbf{J}} \rho_V \left(\frac{V_j^{(min)} - V_j^{(worst)}}{V_j^{(min)}}\right)^2 + \sum_{b\in\mathbf{B}} \rho_I \left(\frac{I_b^{(th,max)} - I_b^{(worst)}}{I_b^{(max)}}\right)^2\right)$$

- Co-existence of reverse power flow and overcurrents

$$f_k(\mathbf{X}) = \left(\frac{RPF_k}{RPF_0} + \frac{OC_k}{OC_0}\right) \cdot \left(1 + \sum_{j\in\mathbf{J}} \rho_V \left(\frac{V_j^{(max)} - V_j^{(worst)}}{V_j^{(max)}}\right)^2 + \sum_{j\in\mathbf{J}} \rho_V \left(\frac{V_j^{(min)} - V_j^{(worst)}}{V_j^{(min)}}\right)^2\right)$$

- Co-existence of reverse power flow and overvoltages

$$f_k(\mathbf{X}) = \left(\frac{RPF_k}{RPF_0} + \frac{OV_k}{OV_0}\right) \cdot \left(1 + \sum_{j\in\mathbf{J}} \rho_V \left(\frac{V_j^{(min)} - V_j^{(worst)}}{V_j^{(min)}}\right)^2 + \sum_{b\in\mathbf{B}} \rho_I \left(\frac{I_b^{(th,max)} - I_b^{(worst)}}{I_b^{(max)}}\right)^2\right)$$

Some hints about the code for solving the transmission system

- The PtG plants have a strength the possibility to change the operation point quite fast
- Thus modelling the variation of RES with respect to an “expected” value is thus important to evaluate also this aspects and exploit the dynamic performance of the system
- For this reason, the code is composed of two Optimal Power Flows (OPFs):
  - The first OPF solves the network by considering the expected hourly values of RES in each cluster
  - The second OPF instead, is run every 10-minutes and solves the network by considering a profile of RES changing every 10 minutes
- The modelling of the 10-minute variability should consider values close to the reality, and thus cannot be model simply adding random values
- An original code have been developed to emulate the variability of the wind, whereas the variability of the PV have been obtained by using synthetic PV profiles provided with time sample 1 minute