The EU Research Project PLANET

Chapter 7

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Abstract

Renewable energy sources offer unprecedented opportunities to reduce greenhouse gas emissions. But some challenges remain to be solved before their full benefits can be reaped. The main one relates to the intermittency of their electricity supply which can lead to grid problems such as congestion and imbalance between generation and demand. Energy conversion and storage has been touted as a very promising solution to all aforementioned issues. PLANET will develop a holistic decision support system for the optimal orchestration of the different energy networks for aggregators and balance responsible parties, policy makers and network operators. It will aid them to leverage innovative energy conversion in alternative carriers and storage technologies in order to explore, identify, evaluate and quantitatively assess optimal grid planning and management strategies for future energy scenarios targetting full energy system decarbonization. Moreover, an analysis of the possible synergies between electricity, gas and heat networks will be carried out by creating simulation models for the integration between energy networks and conversion/storage technologies, for example power-to-gas, power-to-heat and virtual thermal energy storage. Application of the developed tools in two different test cases in Italy and France will showcase their benefits and reveal potential grid stability issues and effective countermeasures.

Keywords: smart grids, synergies between networks, electricity, district heating, natural gas, power-to-gas, power-to-heat, virtual energy storage, network planning tools, grid operation ICT tools

1. Introduction

1.1. The problem and the need

The motivation for this research project stems from the ambitious target setting of the European Commission (EC) to reduce carbon dioxide. Its energy roadmap 2050 [1] suggests that by 2050, the European Union (EU) should cut greenhouse gas emissions to 80% below 1990 levels. Although all sectors—power generation, industry, transport, buildings, construction and agriculture—need to contribute to the low-carbon transition according to their technological and economic potential, the power sector has been identified to have the biggest potential for cutting emissions.

It can almost totally eliminate CO_2 emissions by 2050 (see **Figure 1**) [2]. To meet these aspiring aims, more renewable energy generation (wind, solar, water and biomass or other low-emission sources) is needed. As some of these resources are intermittent like wind and solar, their integration into the power grid calls for apt measures in order not to endanger system stability and reliability.

To accomplish the integration of renewables, there are three measures at hand:

- Enhancement of the grid

  By establishing new power lines and enhancing existing ones, excess electrical energy can be transported from the centres of generation to the centres of demand avoiding bottlenecks.

- Provision and use of flexibility

  Some decentralised energy resources (DER) such as combined heat and power plants (CHP) or an aggregation of them like photovoltaic (PV) systems with batteries and electric vehicles (EV) can provide flexibility to the grid, allowing for balancing generation and demand. By using flexibility of aggregated DER, curtailment of renewables can be avoided, and ancillary services (e.g. frequency and voltage support) can be provided.

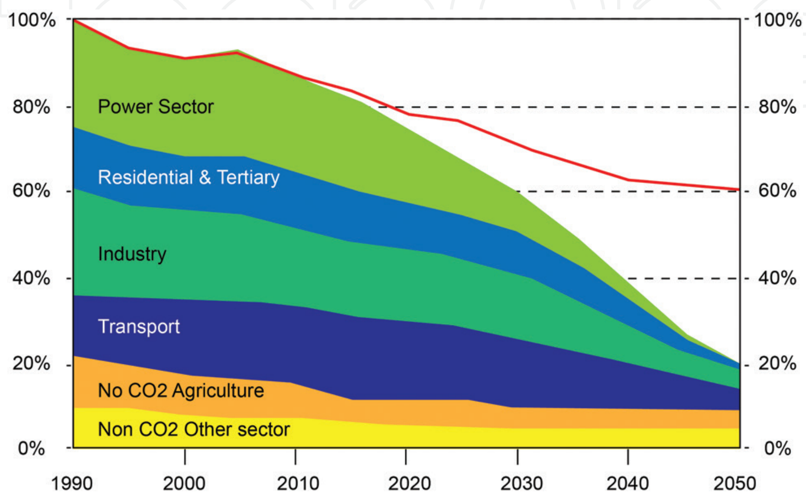

Figure 1. Possible 80% cut in greenhouse gas emissions in the EU (100% = 1990).

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- Storage and conversion of electrical energy

  The current modus operandi of the decoupled electricity/gas/heating networks must be changed in order to allow synergies between the energy networks. Excess electrical energy can be converted into gas or heat and be stored in the respective gas and heat networks. From there it can be used for the purpose of the respective energy network (generation/ provision of heat) or be reconverted in electric energy.

The PLANET project primarily focuses on the conversion of electrical energy and its storage in networks of other energy carriers. By doing so, it will also provide flexibility to the grid. This flexibility can be used for balancing purposes or for offering ancillary services to the grid. Furthermore, PLANET will provide the necessary ICT tools for policy makers and grid planners to guide future network expansion activities by allowing to evaluate if an investment in grid enhancement or conversion technologies or a combination of both is the best solution for today's and future grid challenges.

1.2. The PLANET solution

PLANET will facilitate the grid integration of a broad portfolio of decentralised storage/conversion solutions capable of providing different grid services via a unified and holistic framework for distribution grid planning, operation and management optimization. This solution contributes towards full integration of clean renewable energy resources by exploiting the potential of interconnections and synergies between different energy networks to increase flexibility of electricity demand and to align it with intermittent generation inherent to renewable energy resources. By doing so, it will add to the realisation of the fully integrated EU internal energy market and is of course also apt of being utilised outside the EU.

A functional scheme of this integration is shown in **Figure 2**. It depicts models of the electric grid, the gas network and the district heating (DH) network interconnected by the following conversion technology models:

- power to gas (P2G),
- combined heat and power (CHP), and
- power to heat (P2H) including
  - centralised power to heat (CP2H),
  - local power to heat (LP2H),
  - power to heat (P2H), and
- virtual energy storage (VES).

CP2H refers to heat pumps (or other P2H equipment such as boilers) that are installed at the premises of the DH operator in order to heat the water that goes into the DH grid. LP2H refers to heat pumps that are installed in the premises of customers of the DH grid. Their operation can relieve the DH grid of some heat demand. Although it is in principle possible for LP2H to affect the temperature of the water of the DH grid, it is not intended in the project. Instead, the heat is consumed at the customer premises. VES implies the conversion to heat

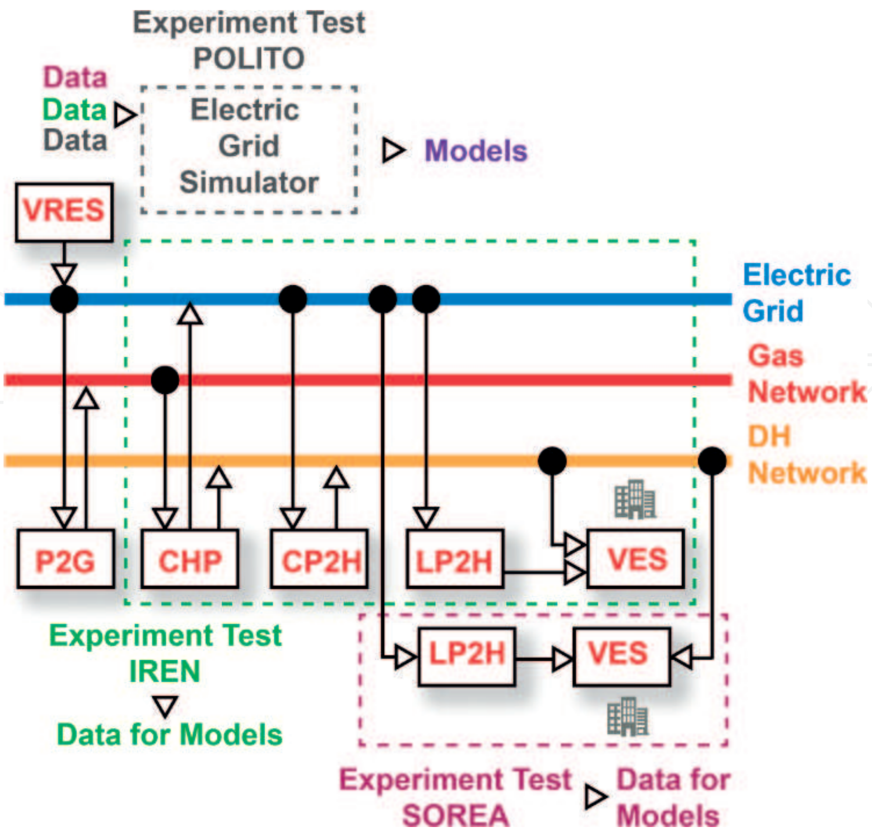

Figure 2. The PLANET energy flows, grid integration and energy conversions.

by means of human-centric thermal management. It leverages the thermal inertia of buildings and installed heating and cooling equipment for the maximum human comfort. Variable and intermittent renewable energy sources (VRES) feed energy into the electric grid. From there, electric energy is converted with one of the conversion technologies, and the transformed energy is fed either into the gas network, the electric grid, or the DH network (indicated by the arrows). In case of CHPs, it is assumed that they are gas-driven and that hence their input energy comes from the gas network. The cogeneration technology allows CHPs to bring synergies among networks as they simultaneously generate heat and electric power that can then be fed into the corresponding heat network and electric grid. Besides, **Figure 2** shows the experimental test sites and their coverage of conversion technology models. These test sites will provide real data for conversion model verification and calibration. Data from the IREN [Italian distribution system operator (DSO)] and SOREA (French DSO) test sites are provided for the Electric Grid Simulator of POLITO (Italian university) which derives models for the networks out of it. The PLANET solution is based on the following four core activity lines:

1. **The modelling of conversion/storage technologies** in order to enable planning, management and operation tools to properly account for their expected impact upon real deployment in the field. These technologies include P2G (high purity methane for direct injection to the gas grid), P2H (including CP2H, LP2H and VES) and CHP (cp. **Figure 2**).
2. **The simulation of the integration between electricity, gas and heat networks models, together with conversion/storage technologies models**, in order to understand how these conversions can affect network stability, reliability and responsiveness.

3. **The development of a holistic decision support system** (DSS) that enables multi-grid operational planning and management taking into account synergies and energy flows between the electricity, gas and heat networks. The purpose is to identify and evaluate optimal strategies to deploy and operate conversion/storage systems on the distribution grids within boundary constraints of real deployments outlined in the future energy system scenarios.
4. **Policy and market model impact assessment and exploration** to evaluate the current regulatory landscape for the deployment of P2G and P2H storage/conversion solutions, as well as policy/market reform recommendations in order to pave the way for their deployment in a technology-neutral manner that ensures maximum benefits to society and the environment. Moreover, an activity of exploration and investigation of novel roles and business models in the energy market will be carried out to pave the way for the commercial exploitation of project results within the opportunities that arise from the existence of PLANET products.

In addition to the aforementioned core PLANET activities, a number of complementary activities will be carried out to investigate and facilitate the adoption and replication of the developed solutions. They include:

1. **Preliminary business planning** to set out initial revenue models and go-to-market strategies for the innovative market actors that will assume the risk of bringing the PLANET solutions to the market through a long maturation process and cost structure improvement, building acceptance in society, establishing appropriate business models and go-to-market strategies and finally developing new products/services.
2. **Pre-design of ICT interfaces to the energy networks and devices** that will deliver grid services (P2G and P2H units, storage units, PCM, CHP units) in order to facilitate their effective operation within the electricity distribution grid in a coordinated manner that will enable the appropriate business actor to deliver valuable grid services.
3. **Definition and promotion of proposals for standardisation bodies** based on the aforementioned interfaces to strive for industrial consensus and to speedier and frictionless adoption by the entire energy system ecosystem, including network operators, equipment vendors, energy retailers, actor marketing conversion/storage solutions, and so on.

2. The PLANET approach

2.1. Concept

Recently, the EU roadmaps outlined the requirement of a slew of technologies and solutions for maximising the capability of the electrical grid to safely host variable and intermittent renewable energy sources (VRES) generation in future energy systems. Actually, the majority of VRES generation in Europe is made available by large, centralised plants (mostly off-shore wind farms) connected to the transmission grid. In the mid-term future, though, the expected proliferation of distributed, variable, small-scale RES systems, aided by extensive policy incentives, can

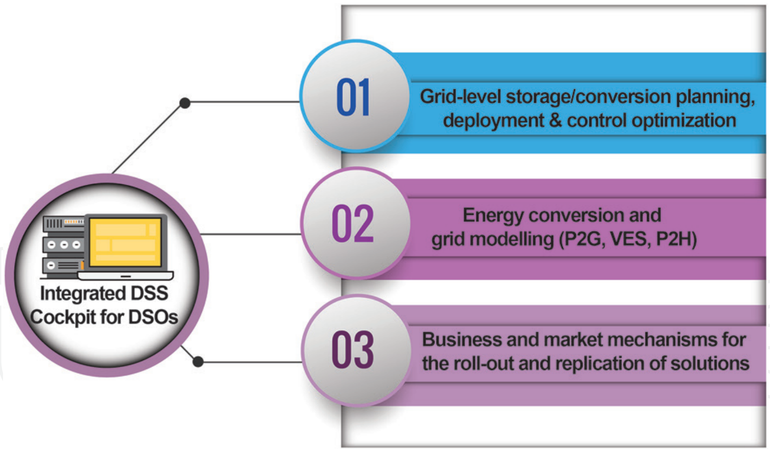

Figure 3. The PLANET concept.

create concern for the distribution grid. Their generation patterns depend directly on weather conditions which tend to be homogeneous across restricted geographical areas. This results in amplification effects that can hamper grid stability and balance. For example, solar irradiance variations in a neighbourhood can be homogeneous resulting in synchronised energy injection in the grid by multiple PV systems hampering grid balance and stability on a very local scale. This example demonstrates the need for decentralised mitigation means. Moreover, significant benefits stem from placing the mitigation means as close as possible to the instability sources in the grid topology. Matching (in terms of proximity in the grid topology) intermittent generation to conversion/storage facility reduces the jeopardised sub-grid area which in turn improves the effectiveness of ancillary services (e.g. reactive power) and DSO grid operation management.

The PLANET project aims at developing a comprehensive solution for the mitigation of critical situations due to decentralised VRES deployment in the distribution grid, towards enabling the elimination of their curtailment and ultimately, the integration of large shares of renewables into the electricity system to achieve the EU energy and environmental objectives for decarbonising the electricity grid and establishing the EU Internal Energy Market. As depicted in **Figure 3**, the PLANET concept consists of the following components:

1. Grid-level storage/conversion planning, deployment and control optimization

PLANET will set up a decision support system that will enable the introduction of storage/conversion solutions in energy system level assessment and evaluation scenarios by authorised energy system actors for network planning, operation and optimization in an integrated and holistic manner. To enhance the representativeness and applicability of the DSS outputs on the actual energy system, real grid constraints will be introduced via a hardware-in-the-loop simulation engine. The heart of this framework is a multi-purpose, district-level optimization software suite with holistic visibility over electricity supply and demand on the grid as well as on the availability and diverse flexibility characteristics of storage/conversion solutions. This suite can be used by network operators to coordinate/orchestrate available flexibility sources (P2H, P2G, VES) for optimal grid operation or by policy makers to evaluate and assess incentives and instruments for maximisation of social welfare and acceleration of policy implementation. Optimization approaches that will be applied include conventional deterministic optimization as well as efficient handling of uncertainty.

2. **Energy conversion and grid modelling (P2G, VES, P2H)**

The three conversion/storage technologies that are in the heart of PLANET activities are already quite mature, ranging from validated research work (VES and P2G) to established technology deployed in the field for decades (P2H). To enable their incorporation in the aforementioned DSS, PLANET will create novel simulation models of these technologies that can be used for fast what-if scenario analysis without compromising on their accuracy for the intended purpose. For P2G conversion, the model will be a high-level abstraction of the detailed simulation process focusing on the electrical interfaces of the conversion infrastructure in order to accurately represent grid interfaces and interactions. For the VES and P2H solutions, the simulation models will be based on the emulation of the actual system working on experimental data collected over a series of demonstration and validation activities that will take place within the project. Again, special emphasis will be given both to the electrical response of the associated devices as well as to the preservation of comfort and indoor healthy conditions. The P2H conversion technologies that will be analysed and modelled will take into account centralised power to heat and local power to heat. CP2H are P2H technologies that can be employed in district heating applications with large-scale thermal storages while LP2H are P2H technologies that can be exploited for the conversion of electricity in thermal energy in decentralised applications where traditional, phase change material (PCM) or VES solutions thermal storage can be applied for the heat conservation.

3. **Business and market mechanisms for the roll-out and replication of the PLANET solutions**

The implementation of the PLANET approach calls for large capital expenditures and new business models to be implemented. Moreover, the implementation of such innovative model needs national regulatory authorities to adopt a new set of rules on energy grids which are intended, on the one hand, to enhance market efficiency and coordination, and, on the other hand, to provide enough incentives to invest to all actors. This part of the project will, therefore, first evaluate business models according to the different possibilities that the regulatory scenario will generate. Each business model will be evaluated using the standard strengths, weaknesses, opportunities and threats (SWOT) analysis. For the business model that will emerge as marketable, we will provide a quantitative assessment using the cost-benefit analysis approach, quantifying the cost of its implementation and the (expected) revenues that it will generate. The second part will be devoted to an institutional comparison between regulatory rules in different EU regions and for different energy services (electricity, gas and heating) with the aim of defining a common regulatory setting and common innovative rules to foster grid investments. This part will involve national regulators, possibly through a questionnaire, and defining a new regulatory approach, which combines two regulatory tools: the first is the engineering-based simulation model developed in PLANET to define ex ante an efficient total network expenditures. The second tool is an incentive-compatible regulatory scheme that should provide ad hoc incentives.

2.2. Methodology

All smart grid actors and stakeholders (network planners and operators, market operators, policy makers, conversion equipment manufacturers and vendors, building managers, citizens, etc.) are collectively placed at the centre of different activities of the PLANET project, which

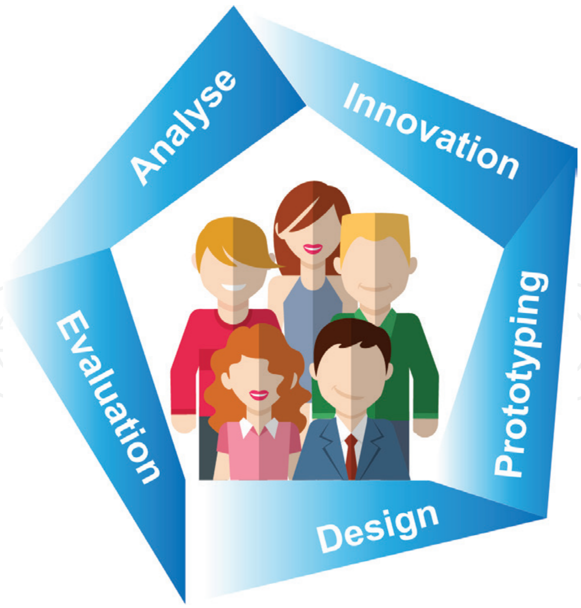

Figure 4. The PLANET user-driven innovation approach.

will adopt a user-driven innovation approach (see **Figure 4**) towards addressing emerging grid, end user and market needs, critical for the successful project implementation and the impacts realization. This user-driven innovation approach intends to involve its stakeholders as active constituents of virtual thermal storage systems as key enablers of the PLANET innovation process and encourages active and collaborative contributions in the development of technological solutions as well as the unique ICT framework for their assessment and grid deployment planning. Agile IT implementation methodologies in conjunction with early validation and verification protocols will be incorporated in the user-driven innovation approach to manage cross-functional teams and facilitate the efficient and proactive communication exchange. Continuous interactions between stakeholders, end users and developers will be encouraged in order to minimise deviations between end users expectations and final outcomes and guarantee the delivery of significant added value both at the level of individual project results (novel storage/conversion technologies, ICT framework) as well as at the level of the unified system which will be ready for use by network operators and policy makers. The proposed **user-driven innovation methodology/approach and activities** will effectively provide an excellent environment for experience sharing and exchange towards user-driven open innovation of products and services. The activities to be carried out will be oriented towards fulfilling the following objectives:

- Disseminate the project outcomes towards end users and various stakeholders to generate a broad awareness and involvement in the project activities.
- Create opportunities for further exploitation and replication of the project results after its official completion in both research and innovation activities.
- Obtain feedback from the end users and interested stakeholders throughout the entire project implementation duration and optimise all project developments, so as to directly address critical needs of end users (network operators, policy makers, etc.) and relevant stakeholders.

To achieve this degree of collaboration, the project will establish a complete awareness and communication framework with all aforementioned end users and stakeholders, including also project partners as main drivers of communication activities. They will be actively involved from the very beginning of concept creation, spurring the motivation to share and discuss their experiences and requirements. This collaborative environment where all the stakeholders co-create the solutions will lead to a natural acceptance by the users who will be empowered not only to test, evaluate and report their own experience with the PLANET technologies and ICT framework, but mainly to start preparing for its adoption in their further research and business activities.

2.3. The PLANET system architecture

Figure 5 depicts the PLANET system architecture. It contains four main functional constituents:

1. Electricity supply module, uncontrollable demand module, virtual energy storage module and power-to-gas conversion module (middle);
2. PLANET SCCE (storage/conversion management and coordination engine) module (top);
3. PLANET IDOC (integrated DSS and orchestration cockpit) (left);
4. Dynamic grid simulation environment including the simulation model generator/integrator (bottom, yellow circle) and the eMEGAsim grid simulation environment (bottom, green circles).

The modules at the middle of the architecture diagram (supply, demand, VES, power-to-gas/heat) are of special importance since they link the PLANET optimization framework with the grid simulator that will validate the project results. Essentially these modules substitute the physical systems for electricity supply, demand, virtual energy storage and conversion systems (P2G, P2H) that will interface with future electricity

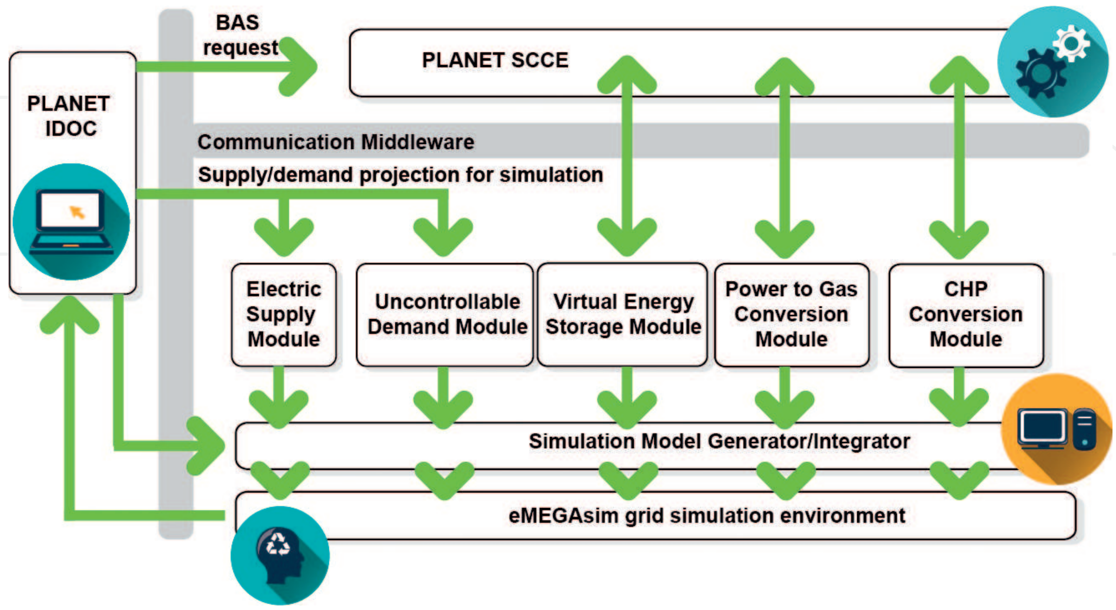

Figure 5. High level system architecture. BAS: balancing/ancillary services for the grid. IDOC: integrated DSS and orchestration cockpit; ISM: instantiated simulation model; M&(O&) C: monitoring and (optimization &) control; SCCE: storage/conversion management and coordination engine; VES: virtual energy storage.

distribution grids. Along with the grid simulator they represent the "physical world" with which the PLANET ICT system (IDOC, SCCE and middleware components) will interact. In order to adequately fulfil this intermediary role, their interfaces need to be very carefully defined. The interfaces towards the grid simulation environment will comprise high-level models of the electrical response of each system, which will then be translated into a simulation model by the generator (e.g. automatically generated Simulink models appropriately configured to exhibit their exact electrical supply/demand response during simulation). The interfaces towards the other system components depend on the nature of the modules.

The "electricity supply" and "uncontrollable demand" modules are the main levers of the PLANET ICT system for setting up the simulation environment with the expected supply/demand characteristics in the selected future energy system scenarios.

The main functional constituents of the PLANET high-level system architecture are described in more detail in the following lines:

1. The **electricity supply module** provides the entire electricity generation perspective to the simulation environment with special emphasis on the modelling of the electricity supply from intermittent VRES and especially small-scale ones. The models will help to understand the real scale of problems to be expected in the coming decades. They will also include the necessary abstract statistical models to forecast generation based on weather forecasts.

   The **uncontrollable demand module** models the expected demand that cannot be directly controlled by the PLANET ICT system, that is, any demand apart from power-to-heat/gas systems. Contrasting this demand with the supply forecast enables the quantification of "excess" supply that should be flexibly consumed/converted by the P2G, P2H and VES systems. Even more importantly, this contrast will also reveal the grid requirements for balancing/ancillary services.

   The **virtual energy storage module** will include a complete, unified representation of the equipment (VES unit) offering thermal storage as well as the building-level control system that will manage it. The latter will be responsible for extracting and aggregating the available demand flexibility of the building as well as the optimal coordination of the equipment based on control commands coming from the SCCE in order to deliver the agreed services to the grid. Moreover, this module contains the high-level VES model that encapsulates the interface behaviour of the VES producing the appropriate electrical response for the provided configuration settings.

   The **power-to-gas/heat conversion module** will perform similar functionality for the power-to-gas/power-to-heat system. Its control system will expose a standards-based interface to the SCCE component in order to receive instructions on how to instantiate energy conversion systems on the simulated grid as well as their operation setpoint for their control. The high-level models for P2G and P2H will encapsulate the interface behaviour of the P2G and P2H systems, respectively, producing the appropriate electrical response for the provided configuration settings.

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2. **PLANET SCCE**: the SCCE component receives the grid needs for balancing and ancillary services and performs a holistic management and coordination across all available conversion/storage options in order to identify how to fulfil the service requests in an optimal manner. The SCCE is divided into the following three functional components:

   BAS request analysis and decomposition module

   This module analyses the grid needs formulated and communicated as a balancing/ancillary service (BAS) request and decomposes them as far as service type, location, time is concerned in order to generate the optimization objectives for the subsequent steps/modules. The decomposition step will perform flexibility allocation to the energy conversion/storage types based on technical and economic efficiency constraints.

   BAS from VES

   This module is in charge of optimally aggregating the available thermal storage capacity to satisfy grid needs in a fashion that is very similar to VPP aggregation and management.

   Energy conversion selection and deployment optimization

   The purpose of this module is to find the optimal way to convert excess electricity that is not used for thermal storage into another energy carrier using the power-to-gas technologies by virtually allocating such systems throughout the distribution grid and coordinating their operation.

3. **PLANET IDOC**: the IDOC component effectively represents the electricity distribution network operator in the PLANET ICT system. It has a complete view on the grid and can directly evaluate and pinpoint potential problems on the grid and subsequently issue requests for balancing/ancillary services. Additionally, it acts as the main user interface to the entire system. It consists of the following five components:

   Grid topology instantiation module

   This module specifies the inputs required for the grid simulation, including the grid topology instance, the detailed scenario regarding intermittent/conventional generation deployment and uncontrollable demand, the sizing and deployment of P2H systems and their connection to the grid, and so on. This information is used to instantiate.

   Simulation results analysis module

   This module interfaces directly with the dynamic grid simulation environment and receives the fine-grain (temporally/spatially on the grid) simulation results for analysis and insights on whether grid stability/imbalance problems (e.g. congestion, frequency deviations) may arise given specific supply and uncontrollable demand sources.

   BAS request generation module

   This module is responsible for generating a request for balancing/ancillary services that is compliant to the communication standard among the IDOC and SCCE component based on the findings of the simulation results analysis.

Process orchestration module

This module's responsibility includes the proper orchestration of all necessary activities for the meaningful and relevant execution of the PLANET ICT system, as specified in the process steps. To achieve this goal, it triggers the remaining system components with appropriate information and oversees the proper functioning of the system.

GUI and visual analytics module

This module comprises the front-end of the PLANET ICT system towards the user. Its feature set allows diverse user types to extract value out the system. For example, a network operator will be able to use the system to evaluate grid reinforcement needs assuming certain penetration of power-to-heat/gas systems in his grid. A policy maker may use it to establish policy instruments to subsidise storage/conversion technology deployment to defer grid reinforcements.

4. The **simulation model generator** component implements an automated method for the coupling of the high-level models of storage/conversion technologies to the dynamic grid simulation environment. Its interface towards the high-level models includes all the necessary information for the instantiation of appropriate models in the simulation framework. This ranges from the number of components and their grid connection location to their electrical response characteristics. This automatic model generation will be based on pre-defined templates for the storage equipment and conversion plants. They will be calibrated using the data provided by the high-level models and instantiated accordingly by generating Simulink components and plugging them in the simulation testbed.

   The **eMEGAsim grid simulation environment** is a real-time, hardware-in-the-loop simulator able to simulate grids at fine-grain time steps.

All communications among PLANET components will be handled by the **Communication Middleware** (grey bar), which will provide the necessary scalability and modularity to the system architecture. It will provide crucial functionalities on top of message routing, such as mediation, service orchestration, protocol conversion, and so on and enhance the interoperability between PLANET components. The middleware will comply with the interfaces to be specified in the project for standardisation purposes and will provide interoperability between them. Furthermore, the middleware will embed data protection and information (cyber-)security measures.

2.4. Models

As described in the PLANET architecture section the modules for electric supply, uncontrollable demand, VES, P2G conversion and P2H conversion comprise high-level models, among them those for P2G, P2H and VES. These models are explained in more detail in this section.

2.4.1. Power-to-gas model

The use of synthetic gases as carriers for excess renewable electricity, known as P2G, offers a solution to manage fluctuating output of renewable energy and mitigating CO_2 emissions at the same time. The storage concept links power and gas networks by the conversion of power into gas by two major steps: hydrogen (H_2) production by water electrolysis and the following conversion of H_2 and carbon dioxide (CO_2) into methane (CH_4) in the Sabatier reaction. Production of synthetic or substitute natural gas (SNG) from CO_2 and H_2 is the advantageous option regarding thermodynamics, which has been demonstrated on an industrial scale at the Audi motor company "e-gas" facility in Werlte (Germany) of 1000 metric tons/year production of SNG from concentrated CO_2 obtained from a nearby biogas plant [3].

The electrochemical analysis will be exploited to develop a simplified high-fidelity model able to investigate optimization options to improve the value of power-to-gas systems to the distribution grid by enabling deployment in proximity to the distributed intermittent generation. During integration optimization, the availability of intermediate outputs and their condition (temperature, pressure) will be explored in order to improve the plant-level conversion efficiency and cost structure. Furthermore, this integration will take into account the energy system boundary conditions for the plant, such as CO_2 availability conditions, electrical supply characteristics and transport capability for SNG in order to optimise the electrolyser capacity. Different electrolysis technologies will be explored, for example, solid oxide electrolysis cells (characterised by high efficiencies, around 90%, but low H_2 production capacities), and Alkaline Electrolyser Cells (which have lower efficiencies, e.g. 75%, but higher H_2 production capacities). The modularity of both electrolysers and methanation reactors, which is necessary to adapt the P2G system throughput to the PLANET requirements, is particularly challenging, given the degree of integration that such two modules could benefit from. Therefore, proper process modelling of the integrated plant, together with reliable dynamic models for the coupling of the electrolyser with the electrical grid, is crucial for the success of the power-to-gas concept.

In particular, the best configuration of electrolysis and methanation coupling will be devised in terms of system efficiency as well as plant size (from 100 kW to 1 MW) and flexibility. Individual component modelling, namely the electrolyser, methanation reactor, heat exchanger network and balance of plant equipment will be simulated using numerical tools (e.g. Apros, Matlab and/or Simulink platform) to perform such integration, and the most suitable technologies will be selected: electrolysers (polymer electrolyte membrane (PEM), solid oxide electrolyser cell (SOEC), alkaline) and methanation (multistage adiabatic and/or isothermal reactors) modules will be investigated in order to resort to the optimal size and efficiency of the power-to-gas plant, selected based on technoeconomic criteria applied to the aforementioned simulated system.

2.4.2. Power-to-heat model

District heating has its roots in the late 1800s with steam-based systems and high temperatures (>200°C). This first-generation system has evolved through two more generations (second and third) characterised with use of pressurised hot water and lower supply temperatures. The discussion of fourth generation district heating grid [1] has raised issues such as new energy sources (e.g. solar, biomass, surplus energy), local production, using buildings as heat storages [4], cooling, heat pumps and ever lower temperature levels (<50–60°C). This evermore complex system poses challenges to its design and operation and in addition, coupling the heating network with gas and electrical grids makes analysis and optimization of the system even more complex. Allegrini et al. [4] reviewed 20 modelling software solutions related to district-scale energy systems and their interactions with focus not only on district heat but also on renewable energy and urban microclimate. They concluded the simulation tools in this field are diverse in terms of data requirements, robustness, accuracy, speed, applicability and ease of use and the no on tools seems to fit all needs. Thus, a two-stage modelling approach combined with data from the pilot site are and ideal combination to be used in the P2H and DH modelling of the project. More precisely, data from the pilot site will aid in the conversion modelling whereas utilisation of a high-fidelity district heating system model (based on Apros [5]) will aid in the DH area.

Furthermore, until now, no integration of power-to-gas solutions with heat grid planning and operation optimization has been done. This area will be advanced in the project, bridging renewable power simultaneously to the gas and heat grids. Two possible power-to-heat conversion applications will be modelled: centralised power-to-heat (CP2H) applications and local power-to-heat (LP2H) applications.

2.4.3. Virtual energy storage model

Virtual energy storage is fundamentally different than the conversion solutions investigated in the project. It represents electricity demand that will fulfil actual human cooling/heating needs that are not bound by energy supply availability. The inherent building thermal inertia—ability to preserve indoor temperature conditions over time—and the availability of electrical heating/cooling equipment with thermal storage capacity (e.g. electrical boilers, heat pumps) provide the leverage to shape the time profile of electricity demand in both magnitude (load turn-up/shedding) and time (load shifting) without sudden and noticeable changes in the occupant ambience. This comfort-preserving flexibility can be almost instantaneously invoked and can reach very large magnitudes, if aggregated over several buildings, offering unique benefits for mitigation of grid instability, and secondarily imbalance. The virtual energy storage module models this flexibility to bridge the gap between the SCCE and the simulation model generator. Since the VES module should provide instances of high-level models of representative buildings—and their aggregated electrical response based on the configuration provided by the SCCE—most internal modelling in the VES module will be performed statistically to enable generation of multiple different, yet representative building instantiations.

The VES module is internally sub-divided into four distinct functionalities. The human-centric comfort preferences modelling component aims to understand and model how building occupants use the facilities and how their thermal comfort is affected by the building characteristics (natural light availability, insulation, etc.) as well as external factors (e.g. seasonal and weather patterns). The main goal of this component is to create user profiles that model thermal comfort by explicitly linking space temperature and comfort (using metrics like comfort elasticity) enabling optimization components to make educated decisions. In addition, it will identify and quantify temperature ranges where humans feel at maximum comfort, hence defining the user comfort flexibility. These models will be calibrated and trained using data that will be captured from real-life (residential/tertiary) buildings offered

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by SOREA under normal operating conditions. In parallel, another component will undertake the modelling of the energy storage elements in terms of thermal and electrical properties. Its purpose is to quantify the thermal capacity and characteristics of buildings including the relevant equipment they host. To achieve this, the dynamic thermal and electrical characteristics of equipment with heat storage properties will be modelled to quantify the effective storage characteristics—for example, thermal capacity and associated electricity consumption, "discharge rate"—given specific environmental conditions. Apart from equipment, dynamic models of the building thermal inertia will also be developed to provide information on the operational context of the equipment. Subsequently these models will be merged to provide thermal storage models for specific building spaces—for example, apartments—that incorporate the properties of the equipment and the host building to yield the combined view on how electricity consumption patterns affect indoor temperature.

By merging the results of the two aforementioned components, the demand flexibility modelling component will calculate the actual acceptable variations in electricity demand that comply with the comfort preferences of building occupants or prespecified allowable comfort degradation. This demand flexibility is completely personalised to the individual user and customised to the specific characteristics of the space he resides in. Alternative user comfort profile templates will be combined with representative building space/amenities combinations in order to generate several possible configurations of context-aware flexibility and cover the diversity of real people living in actual buildings. Finally, the building-level VES optimization component will collect the human-centric flexibility configurations and perform three tasks:

- instantiate a certain building configuration and based on space-level flexibilities assemble the entire suite of flexibility offerings (alternative permissible combinations of demand shifting/shedding/turn-up based on space level demand flexibility) at the building level;
- provide these flexibility options to the SCCE component, which will select one and exercise this configuration option; and
- based on this configuration create the corresponding high-level models with the appropriate building-level electrical response that will be handed over to the simulation model generator component.

2.5. Solution operation steps

To assess conversion/storage at grid level, the following steps are performed between the components of the PLANET system architecture as laid out in the flow chart of **Figure 6**:

1. Step 1: initialization and configuration
2. Step 2: system simulation and imbalance identification
3. Step 3: flexibility dispatch optimization
4. Step 4: real-time monitoring and iterative "on-the-loop" optimization

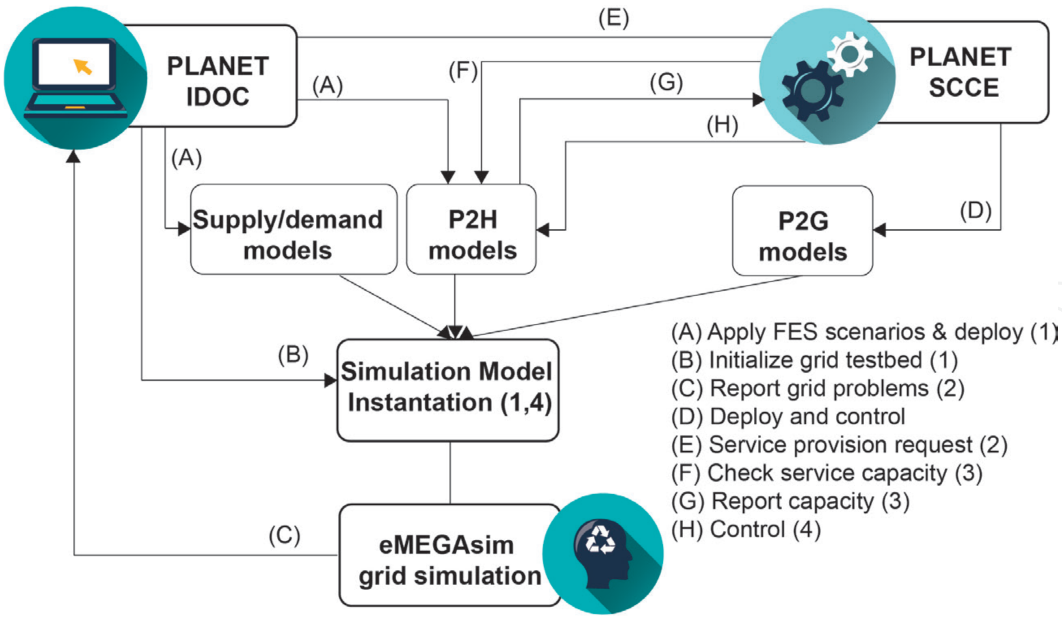

Figure 6. Flow chart of the conversion/storage assessment.

2.5.1. Step 1: initialization and configuration

The ICT system will allow end users (e.g. DSOs), as a first step to select a future energy system (FES) scenario and a network template that will be used for the simulation (A). Based on this information, the IDOC instantiates the simulation testbed with all necessary information including the grid topology and generation, load, storage simulation models (B). The latter can interface directly with the grid simulator and expose the time profile of the electrical behaviour of these devices to the grid including about the location and connection points of these generators/loads on the grid topology. These models include:

- **Conventional and intermittent RES generation facilities**: this model corresponds to the installed RES base according to the FES scenario that is being explored and incorporates all the necessary functionality.
- **Uncontrollable load**: this model corresponds to the electricity loads of the network excluding buildings assumed to be equipped with virtual energy storage capabilities, including conventional buildings, transport-related loads (e.g. EVs), industry/agricultural/commercial loads as applicable to the grid template.
- **Forecasted controllable load of P2H facilities (buildings)**: this corresponds to the intended/forecasted load of the power-to-heat equipped buildings if no grid service provision was required. This will encapsulate human/occupant behaviour and preferences as well as building amenities/equipment.

These last two load models constitute the total load on the grid and they are separated this way to enable the independent modelling of the controllable and uncontrollable loads in the PLANET context. The grid simulator performs a baseline simulation whereby the time profile of energy flows on grid nodes is analysed using power-flow calculations and potential grid issues (congestion, instability and unbalance) are identified and quantified (C).

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2.5.2. Step 2: system simulation and imbalance identification

The information about grid problems is returned from the simulation environment to the IDOC detailing potential imbalances on individual grid nodes/strings. Based on this information, the IDOC generates a request for service delivery by the "flexibility providers" who control storage/conversion facilities on the network topology. This request can be structured upon the template of the FlexRequest of the Universal Smart Energy Framework (USEF) [6] including extensions to incorporate other services additional to the active power flexibility currently covered by USEF.

2.5.3. Step 3: flexibility dispatch optimization

The SCCE module analyses the service request of the IDOC (E) and performs a two-step optimization approach. Initially, the demand flexibility of the power-to-heat is queried from the building-level coordinating modules to establish the amount of services that can be offered (F). Based on the collected information (G), the optimiser performs a fast estimation about remaining service needs and instantiates/allocates power-to-gas units to the grid topology in order to cover the DSO needs entirely. This optimal allocation takes into account a number of relevant constraints, like gas grid proximity, CO_2 availability, proximity to sensitive electricity node (especially important to suppress frequency problems), and so on.

2.5.4. Step 4: real-time monitoring and iterative "on-the-loop" optimization

After the final allocation and usage of P2H and P2G systems is finalised, and it is compliant to the IDOC service request, the optimiser generates the necessary control signals (in function of time to match the service request time schedule) for these systems so that during operation/simulation they offer exactly the required grid services (D, H). The simulation testbed will be updated accordingly, and the IDOC will launch a second simulation round to validate grid stability and balance. During this simulation run, all the simulation models instantiated during initialization and the previous step provide their expected electrical behaviour to the grid so that the new power flow calculations verify that grid problems have been alleviated using these services.

The aforementioned steps largely correspond to standard grid operation planning activities that transcend current energy market/network operations. They are typically performed both day-ahead (based on supply and load forecast models to resolve expected grid imbalances) as well as intra-day (based on the actual demand and supply encountered by the grid to resolve imbalance and/or instability) to counter planning inadequacies in real-time. This incremental grid optimization that is commonplace in grid operations is also inherently supported by the PLANET ICT solution via repetition of the step sequence.

2.6. Market analysis and policy implications

Storage/conversion technologies and dispersed energy generators call for a deep rethinking of current regulatory instruments used to encourage the widespread deployment of green energy generation means. The new policy design must have clear targets and objectives that mix policy solutions to stimulate innovation, environmental sustainability and energy efficiency and provide societal benefits by encouraging unbiased technology deployment, based purely on merits and benefits. Should VES prove technically efficient and cost-effective in mitigating the problems of VRES, policy makers will face significant challenges to design adequate regulatory instruments to incentivise the improvement of the building stock for VES proliferation. The pricing methods and, therefore, the remuneration of DSOs in the presence of demand flexibility is currently a hotly contested topic in the current regulatory debate, but its financial benefits for building owners are expected to be too small to mobilise capital investments. Converting power to gas, on the other hand, effectively shifts the massive decentralised energy generation paradigm from the electricity grid to the gas grid, where it is currently very limited. Policy makers should revisit existing instruments, such as feed-in tariffs for electricity, in light of this shift and investigate whether they should incentivise green electricity generation, carbon-free gas generation or both. Another market/policy side effect of conversion technologies is that they close the loop between the electricity and the natural gas grids and markets. Gas to electricity conversion has long been available, gas-fired plants are widespread.

The emerging ability to purchase electricity and transform it to gas to be sold on the market enables two-way transactions. The relative price of energy carriers (and their volatilities), the conversion efficiency and potential supply security issues are critical factors on how conversion outputs can be used in the energy markets; the structure of the respective markets needs to be examined to verify that they can enforce prevailing regulations given this new capability. Securing funding for policy implementation is another major aspect. There is a stark contrast between the investment structure for grid expansion and storage/conversion system deployment in the grid. The former are financed using funds (indirectly through electricity bills) mostly defined by regulatory bodies since electricity grids provide public utility service. The latter would likely be deployed by private companies through market mechanisms and therefore for profit. Deferred investments on public money cannot directly fund private ventures without skewing competition and violating EU legislation.

To overcome such issues, PLANET will investigate alternative market models/structures as well as regulatory policies for maximising social welfare. It will design and propose a coherent reform recommendation package touching upon both the energy market structure and the necessary regulatory policy instruments to achieve a decarbonised energy system by 2050. The objective of this package will focus on the market integration of VRES generation and storage/conversion technology under fair terms with the ultimate goal to support achievement of the Energy Union targets. This activity will be complemented by an investigation of extensions to market roles and business models that will be required to facilitate the commercial exploitation of the conversion/technology.

3. Results and outlook

The project is at a beginning state, and this means that the consortium is actually working on the elaboration of the potential business cases for the deployment of energy conversion/storage technologies in the European grids, on the investigation of necessary business roles for the successful proliferation of technologies and in identification of PLANET system requirements as an initial step for implementation.

The successful deployment of the global and local level coordination system for power-to-heat and power-to-gas resources depends on seamless information exchange between all actors. This task aims to define the requirements for effective communication and grid interfaces throughout the various system architecture layers to ensure that all necessary information is properly collected and transmitted.

The functional behaviour of the entire system will be finalised and decomposed into the component/module functionalities. Detailed functional decomposition and sequence diagrams will be developed to ensure full interoperability between components. Information exchange and interfaces among (and within functionalities of) components/modules as well as to the outside world will be defined.

Another purpose is to set the requirements and targets that power-to-gas/heat systems should meet so that their decentralised deployment becomes a viable value and business proposition in the future energy systems is fulfilled. PLANET will utilise controllable conversion/storage as flexibility sources for grid balance and stability. To simulate and validate this claim, models of uncontrollable source of electricity demand and supply must be developed as well as projections of heat, gas demand and supply. This to produce the necessary models for energy supply—including conventional generation and variable RES—and uncontrollable demand forecasting in the future energy system scenarios.

4. Conclusions

During the project, PLANET will be also in charge to move the application of the decision support system from a specific network topology towards a more generic network topology. Flexibility in the instantiation of network topologies, selection of conversion and storage options as well as other available infrastructure will ensure the applicability of the tool to very diverse environments and situations that reflect the particularities of grids across Europe. In terms of socio-economics, the ultimate aim of the DSS deployment in real-life scenarios brings opportunities for the further integration of RES-E generation on the electricity grid as well as feeding the gas and heat networks from their oversupply. Long-term side effects of this may include the cost reduction of energy (regardless of carrier), increased security of supply since all generation will be local as well as a significant improvement of social welfare as a direct consequence of these.

Renewable energy sources hold the promise to decarbonise the entire system, including the electricity, heating, gas and transport systems with the use of appropriate conversion and storage technologies. Optimal use of the latter becomes critical in order to achieve the ambitious EU policy objectives of the Energy Union. The PLANET solution will comprise a valuable tool in the arsenal of policy makers and network planners for the coordinated design of networks and compatible policy instruments for the stimulation of the most appropriate technology deployments that can achieve the aforementioned objectives.

Since the annual expected curtailment of solar and onshore wind sources is expected to grow significantly from 29 TWh of electricity in 2030 to 217 TWh curtailed in 2050, the distribution grid should be modified to operate with a higher degree of flexibility. Flexibility sources are required not only for balancing demand and supply, but also for enhancing stability and reliability through voltage/frequency regulation and other ancillary services. Key requirements to achieve proper grid operation include smarter energy grids and enhanced flexibility provided by a wide range of technologies and solutions, such as energy storage, energy conversion and network interconnection, along with demand response.

These solutions will permit a lower use of curtailments, increasing the benefits of RES on the environment. The impact of PLANET outcomes of market transformation will be multifold: initially, the deployment of conversion and storage solutions can reduce the impact of RES generation unpredictability of existing wholesale markets and can relax the necessity for real-time markets giving time to policy makers and the energy system to respond to the new grid challenges. Furthermore, PLANET will provide solutions to encourage and stimulate self-consumption of locally produced electricity in order to isolate intermittency before it becomes a grid problem through a novel human-centric virtual energy storage system that transforms conventional heating/cooling systems into flexible energy resources that respond to local generation or market/grid conditions. The same solution can also become an enabler for the active participation of buildings in energy markets through energy cost optimization or even service provision for grid or energy balancing.

Finally, PLANET facilitates the absorption of electricity exceeding demand from intermittent RES through conversion to alternative energy carriers, such as natural gas or heat/cold, and injection in the respective distribution networks for short-term or even seasonal storage. The PLANET tools enable market actors and regulators to optimally plan, install, commission and dispatch energy conversion units along the electricity distribution grid in order to ensure maximum absorption of excess RES generation and immediate consumption or conversion into alternative carriers.

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