Deliverable 2.1.
Definition of common scenario framework, data/modelling requirements and use cases

Project: PlaMES

Full Title: Integrated Planning of Multi-Energy Systems

Funding: European Commission, Horizon 2020

Project N° 863922

Delivery date: 30/04/2020

Deliverable type: Report

Dissemination level: Public

Editors: Klemens Schumann, Henrik Schwaeppe, Luis Böttcher, Marco Franken, Nicolas Thie, Aldo Bischi, Angelo Gordini, Luca Ferrari, İbrahim Taştan, Michele Monaci

Version 2.0

Issue Date 30. April 2020

HISTORY OF CHANGES

Version 1.0	First version sent to partners, Issue date 30.03.2020
Version 1.1	Feedback from project partners
Version 2.0	Final version

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863922.

TABLE OF CONTENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863922.

1 Executive Summary

This deliverable outlines the general scenario framework, which will be used for the investigations within PlaMES. Therefore, use cases are identified on which the project will be based on. Modelling requirements are derived from the use cases. Furthermore, necessary data to model the use cases is described and potential scenario assumptions are listed.

PlaMES will focus on two use cases, one Central and one Decentral use case. The output of the use cases will be an optimised energy system achieving the climate goals, while including integrated system costs for planning and operation of generation technologies, electricity grid infrastructure and coupled multi-energy sectors.

The Central use case aims to plan the Central Energy System, considering the commodities electricity, gas, heat and mobility. In an integrated expansion approach, generation capacity expansion will be combined with grid expansion. The main target of this optimisation problem is to generate a cost efficient energy system which is compliant with GHG emission (GHG) targets. Results of the first use case will be the planned expansion capacities per grid node and the electrical transmission grid, which is necessary to ensure security of supply.

The Decentral use case will focus on the necessary expansion planning with focus on the Decentral Energy System. Therefore, renewable energy sources and other assets are located in a real distribution grid and an operational planning of this distribution grid is performed on basis of various coordination-mechanisms to minimise Decentral system costs. A distribution network expansion planning is performed to identify optimal grid expansion measures.

The data requirements and scenario frameworks to model the two use cases are listed in a table with explanations and possible data sources.

2 Introduction

The general objective of PlaMES is the development of an integrated planning tool for multi-energy systems on a European scale considering the expansion of both, generation and storage technologies, as well as infrastructure in an integrated manner. Disruptive structural developments are necessary to deliver to the European Union's COP21[1] commitments, as defined by the "Clean Energy for All Europeans" package[2]. Specific targets and measures are identified for the energy performance in buildings, renewable energy, energy efficiency, governance and the electricity market design that envisage an increased cross-border cooperation and mobilisation of public and private investment. Providing European energy system planners with the means to develop efficient strategies to reach these goals is however associated with significant challenges. The scope of the tool that shall be developed in PlaMES is shown in Figure 1.

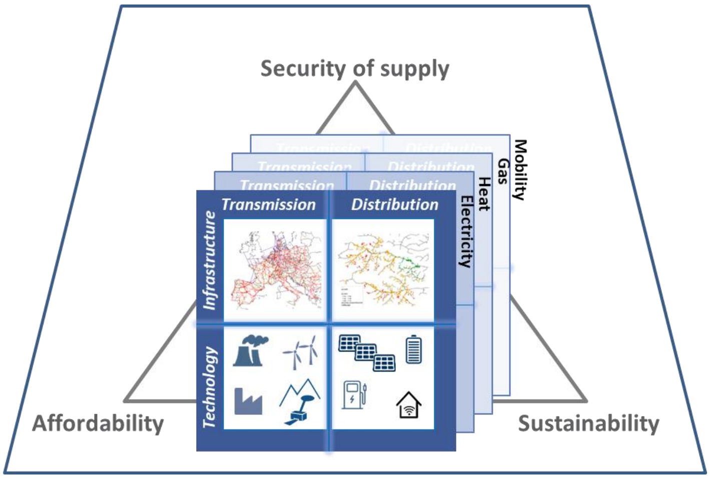

Figure 1: Components and planning principles of a comprehensive planning tool in PlaMES

[1] http://www.cop21paris.org/
[2] https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863922.

This deliverable outlines a general scenario framework, which will be used for all case studies investigated within PlaMES. All case studies intend to determine an optimised energy system for a future scenario. The optimisation is based on the current energy system and aims to determining the least-cost transition towards a setting in the future. Therefore, sufficient data about the current energy system must be compiled to fulfil the modelling requirements derived from interested parties. The scenario framework is a collection of assumptions and hypotheses of uncertainties in the future, which can be varied to analyse possible future scenarios, as well as status-quo data. Therefore, firstly, interested parties are defined and potential use cases for the integrated system planning are deduced. Secondly, requirements for the models that will be developed within PlaMES are derived. Lastly, required data and assumptions to define the scenario framework are presented.

3 Use Cases

Ambitious climate goals require the coupled consideration of multiple energy sectors to provide necessary flexibility to handle higher shares of Renewable Energy Sources (RES), guaranteeing a sufficient electric grid while fulfilling electric, thermal and mobility needs. In order to reach the climate goals, a stepwise reduction of energy related GHG emissions as well as an increase in the share of renewable energies is necessary. For the successful continuation of the energy transition and a reduction of CO2 emissions, the consideration of further sectors besides the electricity sector is necessary. Sector coupling, especially a progressive electrification of heat and mobility energy demands, might have a significant impact on the assumed generation. In any case, it should be noted that sector coupling adds extra flexibility to the system and hence has certain benefits such as the possibility to leverage upon thermal inertia for load shifting on short term bases or gas as chemical storage on long term (seasonal) bases. Altogether, the optimisation of the energy transition comprises adjustments to both, the cross-sectoral technology mix and infrastructure at transmission as well as distribution level.

The energy system can be viewed from a Central or a Decentral perspective. From a central perspective, a large-scale energy system (e.g. one country) requires to be planned as a whole. Central planning focuses on large-scale generation, like central power plants, power to gas plants and wind power plants as well as the transmission grid. Renewable energy plants and most of the loads are located in distribution grids; hence, the distribution grid influences expansion decisions and should be reflected in the best possible way. Sector coupling, in form of electricity based heating and mobility, drives the challenges within the distribution grid and requires sufficient future investments.

The Decentral Energy System (DES) is an inherent part of the Central Energy System (CES), however, a detailed modelling of CES and DES within one planning model is not possible due to the size and mathematical complexity of the resulting model. Therefore, the planning of DES requires an extension of the scenario framework and adds up to two overlapping use cases in the PlaMES tool: a Central and a Decentral use case. However, it must be ensured that the interplay between distribution and transmission technologies is considered in sufficient manner.

3.1 Central Use Case

In the perspective of a central use case, multiple stakeholders and therefore multiple objectives need to be considered.

- Interested stakeholder in planning central energy systems are the operators of the electrical transmission grid, the **transmission system operators** (TSOs). Due to long planning and construction times for new electric transmission lines, a TSO needs to plan grid infrastructure multiple years in advance. To be able to plan the electrical transmission grid for an assumed planning horizon in the future, the grid operator needs to make assumptions about the generation and load at each transmission grid node. For this, the prospective power plant park including information concerning allocation and installed capacity of each power plant are required.
- **Regulators** control and regulate grid operators. When planning to invest into energy infrastructure, the grid operator incurs the costs at his regulator to be able to receive it in the following regulatory timeframe. To determine valuable investments, the regulator needs to have the tools to evaluate central planning measures.

- The PlaMES tool could support **public institutions and policy makers** by analysing policies to steer the system towards climate-neutrality by providing a holistic solution for technology mixes and degrees of grid expansion. This solution could be used as a decision support for decreasing GHG emissions.
- To compete in a market, **original equipment manufacturers** (OEMs) have to specialize in certain sectors or technologies. It is also important to invest in a future relevant technology at an early stage and bring it to market to achieve a high market share. OEMs require knowledge of relevant technologies need benchmarks of their effectiveness. Central planning tools could support OEMs by creating their business plans about future technologies.
- Just like transmission system operators, **gas transport network operators** execute grid planning. Sector coupling and technologies such as power-to-gas could lead to changes in the requirements for the gas transmission network, e.g. impact of higher hydrogen shares in the gas composition. Therefore, a gas network operator needs network planning that also considers other sectors.

The above-mentioned possible use cases originate in multiple questions and issues of multiple stakeholders of a central energy planning. Thereby, the issues of every stakeholder focus on different aspects. Public institutions are interested in a future energy mix that decreases the carbon emissions. For them, transmission network expansion is just a cost factor that has be regarded to sustain reliability when planning the energy system. In contrast, TSOs are mainly interested in the necessary transmission grid expansion. Thereby, the future energy mix and the locational placement of generation capacities are input data that have to be considered in the Transmission Expansion Planning (TEP). Furthermore, central gas system operators are interested in an expansion planning of the gas grid, considering coupling of the electrical and gas sector. However, it is not possible to answer the questions of all possible stakeholders with one tool. Therefore, in the following, two applications that we will focus on in PlaMES are described.

The first application of the central use case is to answer the questions of political public institutions. Therefore, the PlaMES tool shall plan the generation expansion that is necessary to comply with GHG emission targets. This planning should aim for the most cost-efficient planning considering the security of supply. To analyse all possible costs, multiple factors should be considered in the model. Since high potential areas for renewable energies are often remote from load centres, the necessary transmission grid expansion should be considered in the central planning. Many renewable energies are located in the distribution grids. Therefore, the necessary expansion costs of distribution grids should be considered, too. In the future, sector coupling between electricity, gas, heat and mobility will provide potentials to reduce GHG emissions. Therefore, the PlaMES tool should incorporate the gas, heat and the mobility sectors to a necessary degree.

The second application of the central use case of the PlaMES tool is to answer the questions of TSOs. The PlaMES tool should perform a detailed transmission grid expansion planning for a transmission grid operator based on the results of the first application. This means that, given the planned Central Energy System that considers grid expansion costs for the transmission and distribution grid as well as sector coupling, the second application performs a more detailed grid expansion planning. This grid expansion planning should answer the questions which transmission lines should be reinforced. The PlaMES tool should thereby take into account classical expansion technologies as well as power flow controlling devices such as High Voltage Direct Current[3] (HVDC) systems and Flexible Alternating Current Transmission System[4] (FACTS) devices.

3.2 Decentral Use Case

In the perspective of a decentral use case, the following perspectives need to be considered.

- **Distribution system operators (DSOs)** need to ensure a congestion-free network without any voltage range deviations. DSOs have several possibilities. On the one hand, a grid can be expanded by reinforcing overloaded network equipment. On the other hand, flexibilities or smart assets such as voltage regulating

[3] HVDC systems are electrical transmission systems that are operated with direct current. By that, the power flow can be controlled directly and losses can be reduced.

[4] FACTS incorporate multiple control devices which allow controlling power flows in electrical networks or improving system and voltage stability.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863922.

distribution transformers[5] (VRDTs) can be used to reduce grid expansion costs. To take these decisions, distribution grid operators are interested in the amount of renewable supply that could be integrated and loads that could be installed in their grid in future scenarios. Furthermore, DSOs are in need of a tool that enables them to plan the future distribution system while considering the interdependency of multi-energy systems.

- **Regulators** also review the investments of distribution system operators. Therefore, regulators may also be interested in the consequences on the Decentral level (also in combination with central planning).
- In order to make decisions, **regional political and governmental institutions** need information on the regional location of the plants at the Decentral level and the costs of network expansion in the distribution network. Such information can be provided by DES planning.
- At Decentral focus, **utilities** often act as aggregator of electrical load, RES and flexibility. Thereby, they first need to plan the Decentral locations of their plants such as RES or Combined Heat and Power Plants (CHP). Afterwards, they can pool many customers and assets to a portfolio that they can then operate combined. The operational planning can thereby be coordinated in multiple ways by so-called coordination-mechanisms. Examples for coordination-mechanisms are virtual power plants or local energy markets (peer to peer). DES planning could provide utilities with first the locational planning of their assets and secondly the operational planning of their portfolio.
- In many countries, local and district heating networks are operated on a centralised level. Waste heat from industrial processes, waste incinerator plants or CHP plants can be used to heat either nearby building blocks or larger share of the town via larger heat networks. To plan investment, a **heating network operator** is interested in long-term use of its network and plants. Furthermore, future heat sources must be determined. For example, if only gas boilers are shut down for climate policy reasons, a heating network operator may be interested in this information at an early stage to make new investments in CHP plants, biomass boilers or large scale thermal storage.
- **Gas distribution network operators** may also require future energy scenarios in their planning process to evaluate impacts on their infrastructure through sector coupling (electricity, heat, mobility).
- Sector coupling and the new demands of climate change policy will also influence **OEMs** at the Decentral level. The electrification of the mobility sector creates a demand for electric cars and charging stations. New systems such as VRDTs could be installed in distribution networks. The decarbonisation of the electrical sector has an impact on the Decentral power generation and heating systems. To anticipate these trends, an OEM can benefit from planning at the Decentral level.

As in the central use case, the key questions of every potential stakeholder differ. DSOs are interested in planning the electrical grid, while gas distribution network operators are interested in the impact on the gas grid, and operators of heating networks are interested in the consequences for their heating grid. Other stakeholders, such as decision makers, political institutions and OEMs can be interested in a combination of the planning of the three energy networks.

Since it is not possible to answer the questions of all stakeholders in one model, two of them will be focussed on. The first focus is laid on decentral operating utilities. The utilities receive information about the RES that shall be installed in a certain area and need to place them in their area. Afterwards, they require an operational planning of their assets in the decentral energy system. This, in turn, interdepends with the need for electricity distribution grid expansion, matching a use case of a DSO, regulator and local policy maker. Information about the quantity of planned generation and load expansion from the central use case, as well as the distribution and operation within the respective distribution grid influences the grid utilization and can lead to the risk of congestion. Based on this information, the distribution grid expansion is planned to figure out which expansion technologies are the most cost efficient to ensure a congestion free grid. This could be either increasing the grid capacity by new lines or using smart devices and installed flexibilities.

[5] VRDTs are controllable distribution transformers which allow stepping the voltage of distribution networks or long line feeders in an operating system.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863922.

4 Modelling Requirements

Central and Decentral energy system describe the same system, but with a different focal length. Decentral Energy Systems are part of the Central Energy System and can rely on and must contribute to the central one. Within the modelling, DES covers aspects of energy distribution in a granular regional resolution. In contrast, the CES can be understood as the agglomeration of aspects around energy transport or transmission in a transregional resolution.

The distinction can be illustrated by wind turbines which are part of the central as well as the DES. Looking at the Central system, a decision maker is interested in which regions are suitable for wind turbines and whether transmission capacities need to be expanded. Although wind turbines contribute to the Central system, they are installed in distribution networks and must therefore be planned as part of the DES, in which the exact location of the turbines and technical properties determine the network expansion and total cost of integration.

4.1 Modelling targets for planning the Central Energy System

The aim of planning the CES is to determine least-cost energy system designs based on input parameters and scenarios. Target systems determined in this way can help to analyse future energy scenarios and thereby support a decision-making process. From an electrical point of view, the CES consists of locally aggregated, energy resources and loads, large conventional power plants[6] as well as the transmission grid. The Central Energy System not only comprises the electrical system but also further sectors such as the heat sector, the mobility and transport sector as well as the transport and supply of fuels. To reduce the size and complexity of the model, many aspects within this set of systems that could be modelled have been deduced by the relevant and important systemic aspects. In practice, sector coupling related units will be accurately modelled by their electric aspects (e.g., a gas power plant requires gas supply, but the gas grid does not have to be modelled in detail, only capacity constraints and time delays will likely be included).

Three main questions determine the minimal requirements for a modelling approach. The questions are interdependent but give reasons for modelling requirements.

- What is the technology mix of a future energy system?
- What is an efficient localisation for new technologies?
- What is the effort (the total cost of transitioning) to reach an optimised system design?

4.1.1 Technologies of future energy systems

Although several technologies are conceivable in a future energy system, not all potentials will be fully used, as the efficiency of each technology depends on certain systemic conditions. Modelling must reflect all of these potential technologies in the modelling approach.

Conventional Generation

Albeit playing a minor role in the future compared to today, conventional power plants might still be a part of the energy system of the future. Hence, they are an essential part in the modelling. The choice in technologies depends on the availability of fuel types and corresponding generation techniques (steam turbine, simple cycle turbine, combined cycle turbine, etc.), the cost of the installations and for the fuel, efficiency of energy conversion, GHG emission intensity and additional factors.

Renewable Generation

Renewable generation will replace conventional systems in the future in many regards. Energy system planning must reflect the most important technologies of today (wind, solar, bioenergy, tidal, hydro) with their parameters. As new technologies might arise in future (e.g. airborne wind turbines, energy storage technologies), it is necessary to enable easy integration of new technologies to derive their potentials within the modelling framework. The potential of renewable technologies is limited by technology-dependent parameters. Wind turbines and photovoltaic panels need suitable areas for installation. Suitable areas are limited, hence the potential needs to be determined and mirrored into modelling constraints. Feed-in of renewables either depends on external conditions, like wind speed and solar radiation, or can otherwise be steered within certain parameters of storage capacity (run-

[6] Such as nuclear, coal, oil and gas

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863922.

of-river/pondage) and technical parameters (startup-ramps, operational flexibility). The weather-dependent feed-in of renewables also reasons that not only daily feed-in patterns must be reflected in the model, but also seasonal variations of the feed-in. Seasonal variations are also important when considering long-term storage usage.

Sector Coupling

The electrification of heat, transport and mobility requires to be reflected in the modelling. Technologies to be modelled are power-to-gas, power-to-heat and mobility applications. In particular, power-to-gas installations could provide a long term storage of renewable electric energy, via converting it into synthetic methane and fulfil the gas demand still existing. Simultaneously, power-to-gas plants reduce stress on the electrical grid providing long distance transport leveraging upon gas grid infrastructure. Power-to-heat applications - more specifically: heat pumps or electric boilers - have large potentials for greenhouse emission reductions, especially heat pumps due to their high coefficients of performance (ratio between heat produced and electricity consumed far above 1), but might further stress the electrical grid and are therefore essential for the modelling. Lastly, electric mobility also puts stress on the grid, but also offers temporarily available storage.

Storages

Electrical and thermal energy can be stored in various forms. Batteries can provide flexibility for renewable energy, thermal storage, available in certain forms, can store excess heat or be used as seasonal storage. In addition, batteries of electrical vehicles could offer additional storage, used as flexibility when connected to the grid. Within storages, various technologies are available and their versatility must be provided within the modelling, reflecting cost, life-cycles, capacity, efficiency and power input / output.

4.1.2 Localisation of future technologies

To incorporate the electricity transportation task and consider potential congestions, the transmission grid must be part of the energy system modelling. It is conceivable that network modelling might be reduced to remain calculable, but must reflect essential physical boundaries. The network modelling should also cover the possibilities of congestion removal through grid expansion.

The location of renewable energy technologies defines potential feed-in and therefore the cost efficiency of such power plants. Furthermore, technology potentials vary from region to region, depending on available and suitable areas. Conventional power plants also fall under certain restrictions (e.g., cannot be built in high-population-density areas). For any technology, the nodal grid connection capacity must be adequate.

Future sector coupling and supply technologies are mainly going to be installed in the distribution grid. Therefore, the distribution grid would be expanded in such a way that there would be no congestions in the distribution grids. The additional cost must be integrated and evaluated in the modelling or assessed upfront.

Localisation must be reasonably balanced and is an essential part of the modelling. If possible, the resolution of localisation is per grid node. The transport task, the nodal potentials of power plants per area and the cost of distribution grid expansion are essential features.

Lastly, technology expansion and potentials are interdependent with the changes and decisions of their surroundings. If the investigation area is only a section of a larger area (e.g. one country within Europe), the modelling must also incorporate expansion potentials of neighbouring areas.

4.1.3 Reflection of cost

The cost of expansion is an essential input to the model. To have a reliable measure, the existing infrastructure and its operational cost must be considered as well. Investments of future technologies must be incorporated with assumptions for installation (CAPEX) and operational cost (OPEX). The most important restriction for any investment is the emission of GHGs, which must also be reflected in the modelling to enable the modelling of emission-target-proof energy systems.

4.2 Transmission Network Expansion Planning

Within TEP, expansion and congestion management measures are identified for ensuring the required level of system security and reliability of future network structures. TEP approaches aim at minimizing overall system costs including investment costs (CAPEX) and operational costs (OPEX). The identification of expansion measures is based

This project has received funding from the European Union's Horizon 2020
research and innovation programme under grant agreement No 863922.

on the allocation of load and generation units and corresponding time series provided by the planning of the Central Energy System. To reflect technological developments concerning available expansion assets and innovative operation strategies being in the scope of transmission system operators, it is mandatory to investigate classical AC expansion measures as well as power flow controlling technologies in combination with short-term congestion management measures. Therefore, the design of TEP approaches requires a suitable modelling of the investment problem as well as suitable grid operation strategies for flexible and controllable assets to capture interdependencies between available technologies.

In the following, modelling requirements for designing future network structures will be explained with the focus on the base topology and supply task as well as the expansion portfolio.

4.2.1 Topology and supply task

The analysis of power flows and congestion situations within the transmission grid requires a base network model providing data concerning stations as well as transmission corridors and circuits connecting different stations. Each circuit is described by electrical parameters such as the available transmission capacity and corresponding impedances such as the reactance as well as resistance. Further, station-specific information concerning installed transformers as well as phase shifting transformers (PSTs) are also part of the network model. Each asset installed within a station has to be described similarly to circuits by thermal ratings and impedances. Modelling power flow controlling devices such as PSTs requires the definition of corresponding operational flexibilities. Data per station are completed by the connected load and generation units characterized by technical parameters as for example installed or minimum capacity. Assigned load and generation units also include generation units and loads in an aggregated manner, which are installed within underlying network structures. To model the coupling of different energy sectors, locations for power exchange and conversion have to be part of the network model.

Power flows are calculated in hourly resolution based on load and generation patterns required for each load and generation unit. To exploit the benefits provided by power flow controlling devices and further flexibilities, suitable grid operation strategies have to be developed to minimise the need for additional expansion measures and to reduce overall system costs. Furthermore, the quantification of relevant bottlenecks requires an adequate modelling of system security capturing all congestion as well as outage situations being relevant for designing future network structures.

4.2.2 Expansion portfolio

The expansion portfolio contains relevant information concerning technologies taken into account for the TEP modelling. The technologies can be divided into expansion measures as well as congestion management measures. Expansion measures are characterized by the location and dimension of corresponding assets. Congestion management measures are assigned to generation units or assets being already installed within the network and are described by corresponding interventions. Expansion measures require the installation of new assets which are used for resolving bottlenecks over several years and decades while congestion management measures relieve the network only at a single grid snapshot and supply situation, respectively.

To identify suitable and cost-efficient expansion measures for each congestion situation, a detailed technology portfolio has to be modelled. The network expansion portfolio includes classical AC expansion measures divided into expansion and reinforcement measures. Expansion measures contain the development of new transmission corridors providing large transport capacities and reinforcement measures deal with the reinforcement of existing transmission corridors by adding new parallel circuits or by re-wiring existing circuits with high temperature low sag conductors. Furthermore, the reinforcement of substations by additional transformers and switching bays has to be investigated. Compared to the development of new transmission corridors the reinforcement of existing ones is characterised by an increased social and public acceptance. Besides AC measures the placement of power flow controlling technologies such as HVDC systems, PSTs and FACTS devices are analysed. HVDC systems are suitable for bulk transmission of electrical energy over long distances with low losses. PSTs and FACTS (in particular thyristor controlled series compensators (TCSCs)) allow a more efficient utilization of existing transmission capacities by offering operational flexibilities and controlling power flows within electrical transmission grids. Due to utilising existing transmission capacities more efficiently, the need for new transmission lines can be reduced. The consideration of each technology (AC measures as well as power flow controlling technologies) requires the definition of corresponding investment and operational costs as well as parameters for describing the electrical characteristics such as the maximum transmission capacity or operational flexibilities. Furthermore, transmission corridors that can be developed within the TEP approach have to be defined and information concerning the assets that can be constructed per transmission corridor as well as per substation are required. Transmission corridor-specific data contain information about the number of additional circuits, which can be installed, and information about existing circuits, which can be re-wired or upgraded by the voltage level. Station-specific expansion data have to contain data concerning the number of additional transformers and power flow controlling technologies such as PSTs or TCSCs.

Congestion management measures can be modelled as redispatch of conventional power plants, curtailment of renewable energies, the control of power flow controlling devices as well as interventions of further flexibilities such as for example the operation of power-to-gas or power-to-heat units coupling different energy sectors. The potentials of different generation units and facilities providing operational flexibilities have to be calculated based on technical parameters and availability of units to allow an accurate modelling of corresponding flexibilities. Technical parameters contain all those parameters required for describing the grid operation of corresponding units such as for example minimum and installed capacity. Besides technical parameters, marginal costs of each unit are required for calculating resulting congestion management costs. To reflect the regulatory framework of congestion management interventions, the order in which different congestion management potentials should be exploited for resolving congestions has to be modelled accordingly.

4.3 Decentral Energy System

The Decentral Energy System can be seen from two different viewpoints. The first is the cost of Decentral Energy Systems in central planning based on the additional installed generation capacity. This is an input parameter to the central energy system which has been mentioned before. The second is the decentral use case, where the actual planning of one specific Decentral Energy System within one local area takes place.

4.3.1 Decentral Energy System Aggregation (DESA)

While modelling central structures the Decentral Energy System also needs to be considered. The granularity and complexity of the energy system grows with the depth of detail and hence the requirements for the central modelling in PlaMES. The interface between the Central Energy System and the Decentral Energy System gives a feedback from the distribution grid areas to the central planning. An interface between the Central and the Decentral Energy System acts as a streamline for multi-sectoral and infrastructural parameters to picture the underlying area of each Decentral Energy System considered in the Central Energy System.

The streamline process should result in indicators for each area, which represent the investment and operational costs of the installed capacity for each technology considered in the Central Energy System. These indicators can enable the optimisation process in the Central Energy System to consider the cost of the integration of technologies to the existing decentral infrastructure. The process to derive indicators for each area depends on the individual available data. Data pre-processing can provide generation and load time series for all considered technologies as well as synthetic grid data for each area in the Decentral Energy System. It represents the infrastructural status quo of a considered area. To enable Decentral Energy System aggregation, synthetic grid models for status quo supply tasks for each decentral area in a central energy system modelling approach are required.

4.3.2 Decentral Energy System Planning

The decentral use case focuses, in contrast to the Decentral Energy System aggregation, on one specific Decentral Energy System. Overall costs for expansion of generation and load technologies as well as grid expansion within this area need to be determined. This requires a planner to adequately model the interdependent energy infrastructures for a considered area. To ensure the scope of Decentral Energy System planning within PlaMES the operation of the multi-energy supply structures at distribution level, as well as the operational impact on electric distribution grid infrastructure have to be modelled.

Multi-Energy Supply Structures

The DES planning has to consider the same renewable generation technologies (wind, solar, bioenergy, tidal, hydro) and their parameters as the CES planning. The potential of renewable technologies is limited by regionally differing technology-dependent parameters, like possible areas for expansion, wind speed or solar radiation. To ensure the

This project has received funding from the European Union's Horizon 2020
research and innovation programme under grant agreement No 863922.

holistic integrated planning approach for the allocation of future technology expansion, the Decentral integration potential has to match the central integration potential.

Electrification of the thermal and transport sector will play a major role in developing resilient and economic future energy systems. Therefore, the impact of energy carrier interdependent technologies on future energy system has to be modelled adequately, especially in a regional manner. The planning of Decentral generation and sector-coupling technologies require the modelling of coordination-mechanisms which enable the allocation of assets and operational planning. These coordination-mechanisms allow a coordination of energy sources and flexibilities in regional areas. The focus of coordination mechanisms can be economic targets or reducing stress on the electrical distribution grid.

Network Structures

To consider the impact of supply structures on Decentral network structures within the model, Decentral network models are required. Since real Decentral network models are usually not accessible, synthetic network models may be required. In particular, this is the case for the Decentral Energy System aggregation where distribution network models for extensive or even nationwide areas are needed for a representative cost feedback to the central planning. In the Decentral use case, on the other hand, PlaMES will focus on specific network areas. Therefore, it focuses on real network structures that shall be expanded and optimised.

The growing electrification of thermal and transport sectors will have impacts on the planning process of future electric distribution grid. Since electric thermal loads and electric transport loads can have a disruptive effects on the stability of electric distribution grids, PlaMES will focus on planning the electric distribution grid infrastructure while considering electricity, thermal, gas and transport sector.

4.3.3 Decentral Network Expansion Planning (DNEP)

To plan an electric distribution grid in general, it needs to be modelled in a way, in which all generation as well as consumption technologies can be connected to the grid and can generate or consume the maximum contracted electrical energy. This so-called supply task should be approached with the target of maximum economic efficiency with maximum security of supply in the planning process.

Distribution Grid Modelling

To adequately model the electric distribution grid, the grid topology has to be taken into account. The electric distribution grid covers multiple voltage levels from the High Voltage Level (typically 110 kV) over the Medium Voltage Level (typically 30kV/20kV/10kV) down to the Low Voltage Level (less than 1 kV). For each grid level, a typical planning approach consists of the determination of the typical influencing factors such as network equipment data (dimensions and electrical data), list of power consumers (households, consumer trade and services (CTS), industry) and power plants specifications (e.g. wind power plants, photovoltaic power plants, hydro power plants) and their regional distribution. The required factors to model boundary conditions can furthermore be categorized to topological, technological and qualitative conditions. Topology conditions consider the existing grid infrastructure and possible locations for grid expansion measures. Technology conditions describe the network equipment dimensions of transformers, cables, protection and switching devices to ensure security of supply. The qualitative conditions consider the requirements to voltage and current limits in the network. With the assessment of the accessible data the boundary conditions and the supply tasks of the considered area can be derived and are used for the determination of grid expansion measures.

While distribution grid expansion planning has the same economic, qualitative and sustainable objectives on all grid voltage levels, the technological characteristics differ widely across voltage levels.

The high voltage level, which can belong to a DES, represents a supra-regional distribution grid and is usually in a meshed structure in which medium size power stations like wind parks, biomass plants and medium sized hydro power stations are located. In Germany alone, the high voltage level consists of approximately 2700 grid nodes. To model the high voltage level, multiple technologies need to be considered, such as overhead lines, cables, high-voltage switchgears and transformers.

The medium voltage level commonly represents regional distribution grids in open ring structures in which small power stations such as wind power plants or photovoltaic ground-mounted plants are located. Of half a million km

This project has received funding from the European Union's Horizon 2020
research and innovation programme under grant agreement No 863922.

of circle length in Germany, approximately 80% is cable infrastructure and 20% overhead lines, while in other European countries predominantly overhead lines are still the status quo. The modelling of the medium voltage level requires the representation of cable and overhead lines as well as transformer substations and switchgear of the corresponding voltage level.

The low voltage level represents a local, low voltage grid, which secures the supply of each household. In the low voltage level small power stations such as photovoltaic roof plants or new electric loads such as electric vehicles are connected. The low voltage grid is mainly using cable infrastructure, but also overhead lines are used and need to be modelled.

To consider the supply task of network users properly, it is required to model loads in an electric distribution system such as households, industry and CTS as well as sector coupling technologies. Usually, modelling of households is conducted via standard load profiles especially when different grid users are considered in an aggregated way. To derive load profiles for each household, various socio-economic data as well as building information can be used, such as the building type, the building age or the temperature region in which the building is located. This way heat and electricity loads can be determined for the modelling approach. Modelling of CTS as well as industry branches can also be represented through standard load profiles. To derive heat and electricity loads for CTS and industry, the category of the business as well as the number of employees can be taken into account to derive realistic profiles. The electrification of other sectors, especially the heat and mobility sector must be taken into account in developing future scenarios. For the representation of the mobility sector, different rates of electrification can be covered within scenarios. The corresponding electric load can be derived from mobility needs assessed through assumptions about possible future user behaviour. Heat usage from households and CTS can influence the electric grid over the usage of heat pumps or other power-to-heat appliances. The deployment of these technologies within the distribution grid results from the central planning or a scenario specification.

Distribution grid expansion measures

Typically, grid reinforcements for overhead lines, cables and transformers are considered to model the distribution grid expansion. The cost of expansion measures vary depending on the voltage level. Lastly, their impact on the system stability must be evaluated. Taken all together, modelling requires considering operational as well as economic objectives. A cost-minimal expansion decision for the distribution grid has to take necessary network restrictions into account. The grid expansion problem needs to be closely coordinated with the planning of distributed energy supply structures considering energy sector coupling between electricity, gas and heating. The expansion decisions for the electrical distribution grid can include multiple technologies such as the following:

- Grid reinforcement measures
- Grid compatible battery storage systems
- Controllable distribution transformers

While all considered units have a connection to the electrical distribution grid, there are regional differences in the connection to a gas and district heating grid. Depending on the technology decision the impact on each sector needs to be taken into account.

4.3.4 Uncertainties in planning Decentral Energy Systems

Planning DESs requires the consideration of long-term investment decisions, while the possible development of load and generation power at each grid node is uncertain. Although the technical lifetime of equipment in the electricity grid might span several decades, developments in technology, regulation and energy policy can be very disruptive. Moreover, the need for network expansion in medium and low voltage networks is not only due to changes in the load and generation profiles, but also influenced by the location of individual network users. To cover possible future technology paths in the planning process, multiple possibilities and scenarios have to be analysed for what concerns the allocation of load and generation capacities within a network structure.

5 Data Requirements

This chapter will represent the necessary data sets to fulfil the modelling requirements presented in the previous chapter. Data requirements are derived from the modelling requirements and presented in the table below. In contrast to a so-called 'green field' approach, status quo information about power plants, grids and other

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863922.

components is used ('brown field'). Universally, the quality and granularity of data affects the applicability of models. Sophisticated models only come to their full potential with equally substantial data. In return, data only needs to be as granular and detailed as the models require.

In the following, data requirements are being assessed and potential sources for such data are outlined. In case data sources are missing, strategies to obtain alternative input data are suggested. As the choice of data can be a scenario decision by itself (such as the weather conditions), scenario assumptions for a scenario framework are also being determined. Data, potentially restricted by intellectual property, is marked with [IP].

Requirements	**Description**	**Potential Source**
Time Series		
Electrical load profiles	Electrical load profiles for each grid node. For CES the electrical load profiles are required for each grid node of the voltage level that is considered, e.g. the extra high voltage grid in the focus region. For the peripheral regions, load profiles for each country are required. For the DES, the electrical load profiles need to have a granularity of at least medium voltage substations. If the distribution grid shall be planned per building, electrical load profiles are required for each household, business and industry. Both, the electric load profiles of CES as well as DES, depend on the load of the sectors households, commerce, trade and service and industry. Even if the profiles are required on an extra high voltage grid node granularity, a change of the energy demand of one of these sectors has a high impact on these load profiles. The load profiles need to have a granularity of at least one hour.	[IP] Bottom-up modelling based on existing models of RWTH Aachen University (C. Müller et al., Modeling framework for planning and operation of multi-modal energy systems in the case of Germany, Applied Energy, Volume 250, 2019 https://doi.org/10.1016/j.apenergy.2019.05.094) Entso-E standard load profiles for each country (https://www.entsoe.eu/) TYNDP (https://tyndp.entsoe.eu/) [IP]* Data delivered by potential third party (DSO) (*depends)
Electrical charging demand in mobility and transport	Although being a part of electrical load profiles, data for charging of electrical vehicles are mentioned separately. Several methods exist to determine electrical charging profiles, therefore also more than one database can be used to achieve this. One can either directly use charging data or types of mobility studies. Depending on the data, assumptions must be made regarding the total energy charged, the size of storages, the charging times and durations or the distance driven (per person, per average ride).	"Mobilität in Deutschland" - German mobility study with typical mobility behaviour in Germany; could be applied to Germany https://www.bmvi.de/SharedDocs/DE/Artikel/G/mobilitaet-in-deutschland.html [IP]* Data delivered by potential third party (DSO) (*depends)
Thermal load profiles	Thermal load profiles for each grid node. The electrical load is depending on the thermal load profiles and the heating technologies that are used. If the heating technologies of each building shall be planned by the PlaMES tool, the thermal load profiles	[IP] Bottom-up modelling based on existing models (C. Müller et al., Modeling framework for planning and operation of multi-modal energy systems in the case of Germany, Applied Energy, Volume 250, 2019,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863922.

	have a direct impact on the electrical load in the optimisation problem. Therefore, thermal load profiles per grid node are required in the same granularity as the electrical load profiles.	https://doi.org/10.1016/j.apenergy.2019.05.094)
Annual energy demand	To consider the demographic and technical developments up to the scenario year, the electric and thermal load profiles can be scaled to a predicted annual energy demand for electrical and thermal loads in each sector households, CTS and industry. This can be one value for each country and each sector for one year.	Potencia https://ec.europa.eu/jrc/en/potencia TYNDP2020 https://tyndp.entsoe.eu/
Weather related data	For the determination of hourly feed-in time series the local conditions of i.e. wind speed and irradiation are considered in combination with reference time series for renewable energies. The modelling of the use of biomass and run-of-river plants as well as CHP and landfill/sewage gas plants is carried out under consideration of pre-determined estimations, i.e. expected full load hours.	
Wind data	To generate region-specific feed-in profiles from wind turbines and other wind-dependent technologies, wind data is required. Weather data should have at least hourly resolution and a suitable spatial resolution (at least covering data for a 20 x 20 km grid).	ERA5 dataset (successor of formerly known ERA-Int) https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5 COSMO model reanalysis dataset https://reanalysis.meteo.uni-bonn.de/
Solar radiation data	Solar radiation to derive photovoltaic and other radiation-dependent electrical feed-in or thermal allocation. Should comprise disturbances like blocked radiation from clouds and so forth.	
Wind turbine feed-in profiles	To generate time-series from wind data, turbine profiles are needed. Plenty of data sets, also considering different hub heights, are available. The considered turbine curve characteristics are an assumption themselves, but should be derived somehow and explain the feed-in from 0 to at least 25 m/s, better 30 m/s.	Turbine feed-in profiles have been published without restrictions at http://www.wind-power-program.com/download.htm#database Usage is claimed to be free, without detailed licensing information. Another framework is provided by windpowerlib https://github.com/wind-python/windpowerlib
Network Models		
Electric Transmission Network Model	Base network model providing data concerning stations as well as transmission corridors and circuits connecting different stations. Each station must be described by a geographic location.	[IP] Transmission grid model of RWTH Aachen University

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863922.

	Each circuit must be described by electrical parameters such as the available transmission capacity and corresponding impedances such as the reactance as well as resistance. In case of specific investigations, a list of potential transmission grid expansion measures must be provided.	SciGrid - Open Source Reference Model of European Transmission Networks for Scientific Analysis https://www.power.scigrid.de/ PyPSA-Eur: An Open Optimisation Model of the European Transmission System (Dataset) https://zenodo.org/record/3601882 Data delivered by potential third party (national TSOs, ENTSO-E)
Electric Distribution Network Model	To determine the Decentral electric grid expansion measures for the central planning within PlaMES, in medium voltage (MV) and low voltage (LV) levels, synthetic grid models need to be used, since no real grid model data is available for the distribution grids. These characteristic synthetic grid models need to represent the heterogeneity of the supply task as well as the grid structure of the considered areas. For the modelling of MV and LV grids, regional differences in land use and supply task need to be analysed and clustered to representative areas (e.g. suburb, city, rural). Based on the supply task and the regional characteristics, synthetic distribution grids for the respective regions could be created with the help of a grid generator or synthetic benchmark grids will be used. To enable the modelling of MV and LV networks in PlaMES the status quo supply task of each area is necessary. For the DES planning of a DSO the real grid data will be needed.	[IP] High Voltage Grid Model of RWTH Aachen University [IP] Distribution Network Generator Tool of RWTH Aachen University Open Source Grid Models (e.g. SimBench https://simbench.de/de/) [IP]* Data delivered by potential third party (DSO) (*depends)
Network transfer capacities	If the transmission grid is not available for each country and their interconnectors, all countries except the focus region can be represented as one node. Then these one-node countries can be connected by their existing network transfer capacities. These need to be provided as a matrix with a capacity (MW) for each two neighbouring countries.	Entso-E (https://www.entsoe.eu/) TYNDP (https://tyndp.entsoe.eu/) National network development plans
Power plants		
Status Quo power plants	The PlaMES tool will plan the energy system in a brown field approach that will consider a status quo of the power plants. Therefore, this status quo needs to be an input to the PlaMES tool. Current power plants need to be known.	[IP] RWTH Aachen database [IP]* TSO Databases (*depends)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863922.

	For each power plant that will be in operation in the scenario year, the technical parameters and their location need to be known. Technical parameters include minimal and maximal power, ramps, efficiencies, GHG emissions, costs maintenance, minimal runtimes and annual downtimes for maintenance. The location needs to be known in a grid-node granularity.	Database of network development plans of each country German federal network agency [IP] Third Parties (PLATTS World Electric Power Plant Database, Windfarm Database)
Technical Parameters future technologies	Future power plants and other technologies (e.g. Fuel Cells, high temparture heat pumps) have certain parameters that are required to model them and their differences. These parameters are ▪ Maximum power ▪ Minimal power ▪ Ramps ▪ Efficiencies ▪ Maintenance costs ▪ Maintenance times ▪ Minimal run times ▪ Greenhouse gas emissions	“Technology Data for Energy Plants”, Danish Energy Agency, 2012, last update July 2018. https://ens.dk/sites/ens.dk/files/Analyser/technologydata_for_energy_plants_-_may_2012_ver_sep2018.pdf “Technology Data for Energy Plants for Electricity and District heating generation”, Danish Energy Agency, 2016, last update October 2018, https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_el_and_dh_-_aug_2016_upd_oct18.pdf Should be revised in scenario framework
Fuel prices	Prices for each energy source are required to consider different electricity generation costs. Fuel prices especially determine the cost of conventional power plants and therefore are input data and scenario assumption at the same time. Besides guesses, fuel prices can be matched to external scenarios that match the current one.	IEA World Energy Outlook National Grid Development Plans TYNDP (https://tyndp.entsoe.eu/) Potencia (https://ec.europa.eu/jrc/en/potencia)
Spatial data		
Land usage / coverage	Detailed modelling of placing of assets can be supported by current land use data sets. Such data is provided by the CORINE land cover dataset, but could be replaced through other datasets as well. Land usage is needed to allocate or determine RES potentials in certain areas.	CORINE Land Cover (CLC) https://land.copernicus.eu/pan-european/corine-land-cover
Power plant potential areas	Areas in that new power plants can be installed, e.g. polygons or power potential per region	[IP] RWTH Aachen models
District Heating		

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 863922.

District Heating	One way to have heating in buildings is to use District Heating (DH). District heating can be supplied with heat by CHPs, waste incinerator or waste heat from industrial processes as well as electric boilers and industrial heat pumps (in case of low temperature networks) in order to have electricity conversion into heat (P2H). However, the DH infrastructure needs to be built, in many regions, it exists but in others will be object of an economic trade-off between CAPEX and revenues. These heat grids need to be known to represent them in the PlaMES tool. The heat grids need to have a household sharp granularity.	[IP] RWTH Aachen model [IP] OPTIT model Heatroadmap (https://heatroadmap.eu)

6 Scenario Framework

In energy system planning, there might be some certain future parameters, and some uncertain future parameters. The certain parameters have been described in the data requirements. One example is the status quo transmission grid. Since in the central use case, the necessary grid expansion shall be planned and we will use a brown field approach in PlaMES, a start grid needs to be stated. This expansion grid model is known in the time of the planning. It already exists and already planned expansions for the next ten years are known as well.

Uncertain parameters can be prices for fuels. Since they are not known for the future, we have to make assumptions about those values. These uncertain parameters will be described in this chapter.

The process of the energy system planning consists of several steps that should frame the same scenario altogether. To ensure a common scenario, a scenario framework is defined.

6.1 Determining a scenario

A method for creating systemic scenarios must be applied. PlaMES obtains the expertise and experience of the project partners as well as the assessment of the Advisory Board. To develop consistent scenarios, the mutual interactions between the different factors influencing the energy system must be identified and taken into account. By planning an energy system in the distant future, a high uncertainty of the possible development has to be reflected in the scenarios. A scenario framework also helps to validate the scenario assumptions altogether and specify parameters that need to be elaborated.

The process of the scenario creation for the Decentral use case is congruent to the process of the central use case, but can be adapted, depending on the application. While CES will provide an optimised solution for the integration of technologies in an area underlying a transmission grid node, this solution can be used as a scenario input for the calculation of the Decentral use case. However, since the solution for CES may not represent the individual planning objectives of a DSO, the DES scenarios can be altered individually.

The scenario creation for deriving the costs of distribution grids must reflect the future possible technological combinations in generation and load. The scenario framework for calculating the aggregated costs of the distribution grid expansion must be the same as for the CES planning.

6.2 Assumptions per scenario

weather data	a) Choose specific weather-year or use synthetic weather data b) full load hours per technology if weather-dependent
fuels	c) prices d) specific CO_2 emissions e) import capacities

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863922.

emission budgets	f) especially CO_2, but other emissions can be targeted g) emission budget per sector, per country etc.
final energy demand	h) in households a. space heating [TWh / year] b. warm water [TWh / year] c. electrical demand [TWh / year] d. technology supply structure [% of heating] i) in commerce, trade, services a. heat demand [TWh / year] b. electrical demand [TWh / year] c. technology supply structure [% of heating] j) in industries a. warm water / process heating (per temperature class) [TWh / year] b. electrical demand [TWh / year] c. technology supply structure (per temperature class) [% of heating] k) in mobility / transport a. kilometres per person and motorcar b. kilometres in transport c. electrical share l) district heating a. potential share of heat demand that could be supplied by district heating
technologies	m) existing (pre-)installed capacity of conventionals / renewables n) potential areas for building new power plants (conventionals and renewables) o) distances to buildings for renewables, in particular wind turbines p) non-pollution areas for combustion power plants q) Cost for using certain technologies (CAPEX, OPEX) r) minimal installation or production requirements (e.g. electrolysers for H_2) to find suitable locations
electrical grid	s) which grid to use as a starting point (which expansion measures to include) t) electrical import/export capability for areas not in focus u) potential expansion measures v) cost for expansion measures (capacity-, project- or component-wise)
Electric network planning principles	w) voltage level specific x) radial/ring/mashed network structures (e.g. depending on load density) y) influence of supply task z) type of technologies used for expansion planning aa) planning principles to achieve requirements for secure grid operation for voltage changes, interruption of supply, frequency, overvoltages, asymmetries and harmonics bb) planning horizon cc) n-1 system security
Demand side management	dd) potential for industrial demand side management in each country [MW] ee) potential shifting time of industrial demand side management [h] ff) price of industrial demand side management [€/MWh]

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863922.

7 Conclusion & Outlook

In the central use case, questions of political and public institutions as well as TSOs are going to be answered. The PlaMES tool will carry out an energy system planning, which will plan for a future energy system in an integrated manner, generation capacities and transmission capacities, taking into account the EU energy trilemma. The Decentral use case will give answers to questions of a DSO. For this purpose, a future distribution network is planned; taking into account possible voltage band violations and line overloads caused by electric mobility and distributed generation.

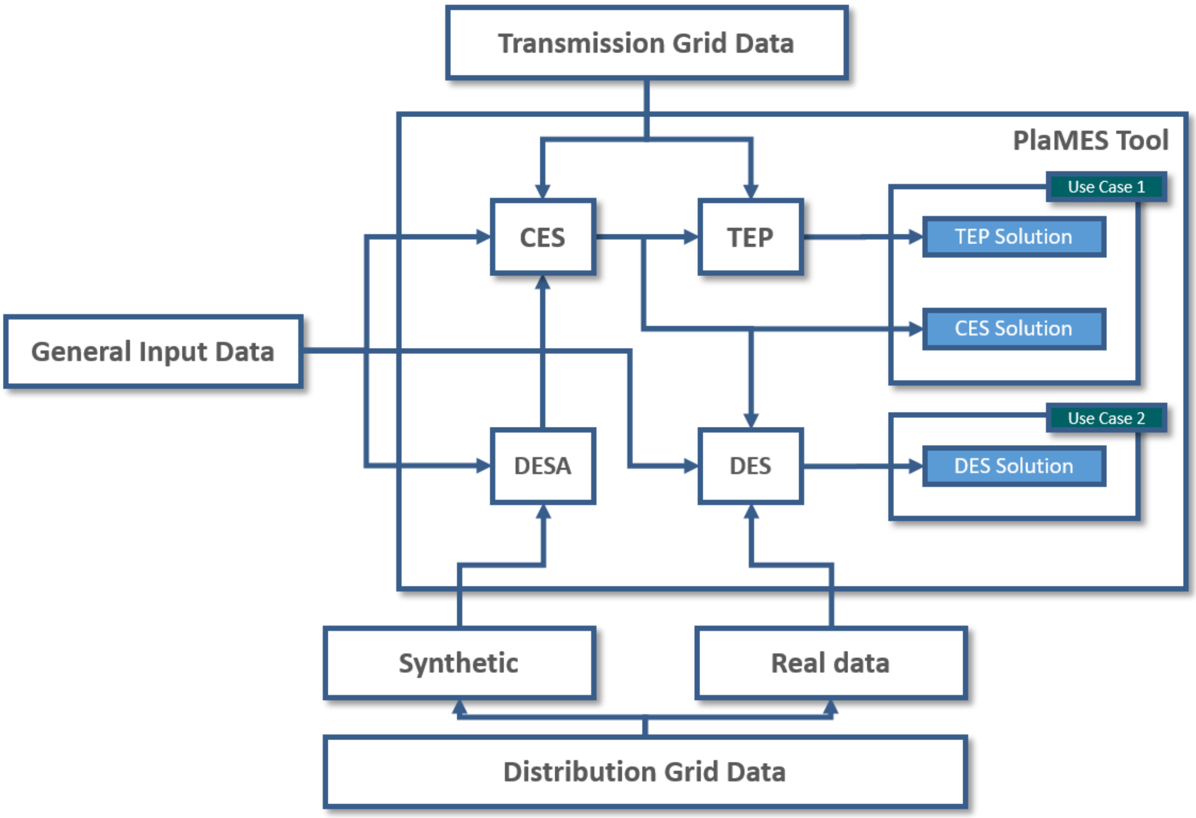

Figure 2: Relational block diagram of input-data, tools and use case definitions.

In the following, a mathematical formulation of the PlaMES tool will be developed. A basic approach of the model is illustrated in Figure 2. The input data can be differentiated into general input, transmission grid data and distribution grid data. Distribution grid data can be either synthetic models or real grid data. While synthetic grid data can be used for DESA, DNEP requires real grid data.

To solve the central use case of PlaMES, three submodules are used. DESA estimates costs for each Decentral Energy System by performing a network expansion heuristic with different penetrations of renewable energies. The result of this model can then be used in central planning. In a fully linearized approach, CES plans the Central Energy System, taking data from DESA and the transmission grid into account. The result of the CES will then be given to the TEP. It will focus on a detailed expansion planning approach analysing different expansion technologies and congestion management interventions. DES undertakes the locating of renewable energy sources for a decentral energy system, an operational planning and distribution network expansion planning and can be enriched by information from CES.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863922.