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Framework for Modelling Investment
and Operation of Energy Systems at
European Level**

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A Novel Modular Optimization Framework for Modelling Investment and Operation of Energy Systems at European Level

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ABSTRACT

Project plan4res (www.plan4res.eu) involves the development of a modular framework for the modeling and analysis of energy system strategies at the European level. It will include models describing the investment and operation decisions for a wide variety of technologies related to electricity and non-electricity energy sectors across generation, consumption, transmission and distribution. The modularity of the framework allows for detailed modelling of major areas of energy systems that can help stakeholders from different backgrounds to focus on specific topics related to the energy landscape in Europe and to receive relevant outputs and insights tailored to their needs. The current paper presents a qualitative description of key concepts and methods of the novel modular optimization framework and provides insights into the corresponding energy landscape.

INTRODUCTION

In pursuit of the decarbonization targets stated at the COP21 Paris Agreement [1], many European countries have declared national energy agendas [2] up to now predominantly focusing on the integration of solar photovoltaic (PV) and wind power. This has contributed to a significant increase in electricity generation from renewable energy sources (RES), which is reaching shares of more than 30% in electricity consumption [3]. Also, while renewable capacity has traditionally been installed alongside historically developed thermal generation fleets, recent announcements about planned decommissioning of coal and nuclear power plants [4-6] are about to transition Europe's energy landscape into a new phase in which electricity systems will be characterized by the combination of significantly reduced capacity of fully-dispatchable units along with increased shares of volatile RES. Such developments can create significant challenges for national energy systems over the coming decades. Addressing them will be fundamental for ensuring secure and reliable energy supply for every European country in an efficient and cost-optimal way.

Over the coming decades the European power system is likely to experience further integration of RES combined with reduced thermal capacity due to widespread decommissioning of power plants and increased electrification of key sectors of the economy. Such developments have the potential to challenge the energy system, especially considering the cost-efficient and reliable system operation.

A. DECOMMISSIONING OF THERMAL POWER PLANT CAPACITY

Recently announced plans for the decommissioning of thermal power plants in six European countries account for a reduction in coal capacity of around 53 GW and in nuclear capacity of around 26 GW by the year 2035 (see Table 1). If such decommissioning plans are realized, they will lead to approximately 11% reduction in the installed, fully-dispatchable power plant capacity in Europe by 2035.

reduction target		FR	DE	UK	ES	NL	IT
coal	2020-25	2.9	13	4.8			7
	2026-35	-	17	-	3.9 ^d	4.6	-
nuclear	2020-25		8.1	-			-
	2026-35	10	-	-	7.1 ^d	0.5	-

Table 1 Announced coal and nuclear power plant reduction plans in GW_{inst} per country (source [3-7])^d: under discussion.

As a result, there will be a significant shift in the balance between fully dispatchable capacity and volatile RES given the expected doubling of RES capacity by 2030 [3-5].

Such developments may pose risks to the security of electricity supply due to the eventual fundamental dependence on volatile RES. In light of this prospect, some European countries are considering increasing their reliance on cross-border electricity imports as a potential way of maintaining high levels of security of supply during extraordinary peak demand. However, the potential contribution of cross-border exchange of electricity to ensure the

security of supply needs to be examined in more detail. For example, there may be periods during which neighboring countries may experience the occurrence of similar ‘calm’ weather conditions, which may lead to a low output from wind farms. During such ‘calm’ periods, cross-border electricity exchange may not be in the position to supply sufficient amounts of energy since RES will play a dominant role in the energy mix of neighboring countries. Thus, investment in additional flexibility measures will be required, including energy storage and demand side response.

In conclusion, the reduction of fully dispatchable thermal capacity coupled with increased capacity of volatile RES is bound to create significant challenges for the future pan-European energy system.

B. ELECTRIFICATION OF HEATING AND MOBILITY

The ongoing electrification of the heat and transport sectors constitutes a significant part of the global decarbonization effort aiming to reduce greenhouse gas emissions. However, the decarbonization of these sectors will have a considerable effect on the energy system operation. For example, although electrification of heating (power2heat) technologies in combination with heat storage may bring more flexibility to system operation, they can also induce some additional seasonal peak in the electricity demand, and accept the following increased demand for electrical space heating, which is particularly high during extreme cold periods (see, e.g. [8]) during which the heat pump equipment exhibits reduced efficiency as well.

Similarly, the electrification of mobility, which is mainly achieved through the adoption of battery electric vehicles (BEV), may also bring the benefit of additional flexibility to system operation. Nevertheless, their integration may potentially also induce higher electricity demand during charging periods, thereby placing extra stress to system operation unless charging is done in a ‘smart’ manner.

C. THE NEED FOR A HOLISTIC APPROACH TO CO₂ POLICY

CO₂ pricing and taxation constitute a significant lever to further push decarbonization as they create incentives for a more environmentally friendly energy strategy. On this basis, European-wide trading of CO₂ emission allowance (ETS / EUA) was introduced, but its effectiveness was restricted by the low price level that lasted until 2017. Since 2018, the prices for ETS / EUA changed and have remained well within the current target range of 20€ to 30€ per ton CO₂. However, currently, ETS / EUA do not find application to all energy-related sectors and are not implemented across all European countries. Instead, manifold national energy-related taxation exists, and, in some cases, it does not consider CO₂ emissions.

Pursuing an effective CO₂ policy across Europe may possibly be accomplished within a framework that ensures that there is sufficient coordination among countries in terms of the implemented CO₂ policies and that application is guaranteed to all energy-related sectors.

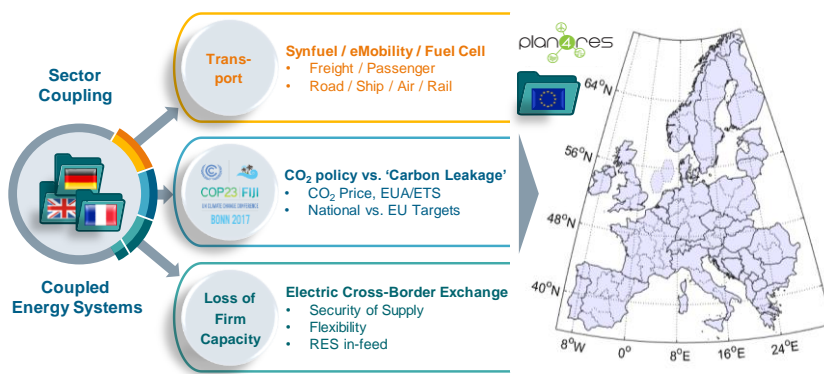


Figure 1. Topics relevant to decarbonization that require a pan-European approach: Electrification of transport, comprehensive CO₂ policy and reliable electricity cross-border exchange to counter the loss of fully-flexible thermal capacity.

THE SCOPE OF THE PLAN4RES PROJECT

The above-mentioned topics indicate that the challenges associated with the described developments are so significant that there is a considerable need for pan-European alignment of the national energy strategies. Ideally, this alignment will apply across all energy sectors including the heat and transport sectors as well as the cross-border energy exchange.

In the context of the plan4res project [9], a modular optimization framework will be developed, which will display the seamless alignment of different stakeholders' perspectives across various energy sectors; stakeholders can include TSOs, DSOs, utilities, authorities and investors. Specifically, this framework will consist of optimization modules or models, each representing operation and investment within a specific energy sector and at different levels of detail (see [10]). Therefore, the framework will allow focus on specific topics of interest depending on the requirements of the stakeholder.

In order to demonstrate the capabilities of this plan4res framework, the aforementioned modules will find application to three case studies (Figure 2), each focusing on a different perspective of a sustainable energy system:

- I. Multimodal European energy concept considering the sector coupling of electricity, heat, mobility and gas.
- II. Strategic development of the pan-European network considering long-term sources of uncertainty.
- III. Cost of RES integration and impact of climate change in a future European electricity system with high shares of RES.

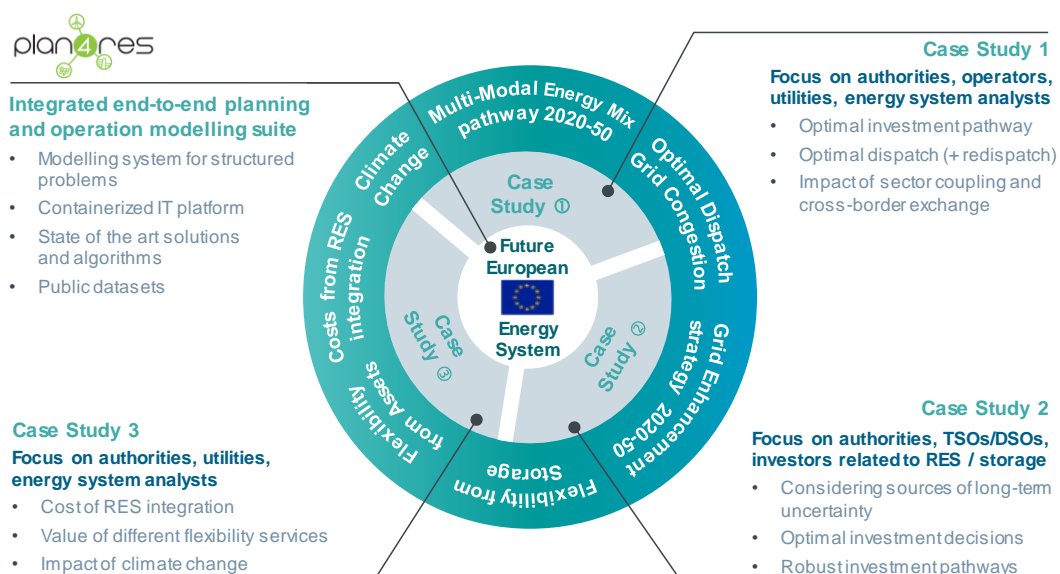


Figure 2. Illustration of the plan4res modular framework and the scope of plan4res case studies.

Each case study (for detailed description see [11]) comprises scenarios that highlight different perspectives of the future energy system including the effect of technological advances, the pace of demand growth and the evolution of wind and solar PV capacity. In addition, embedded transformation tools enable the aggregation or disaggregation of data at different temporal or regional resolution and facilitate the re-use of results among modelers and stakeholders.

Additionally, in the plan4res project, an illustrative workflow is applied to the aforementioned three case studies, combining them to a joint modelling approach applicable to the pan-European Energy System. This workflow comprises five interacting steps (Figure 3) and, through the case studies, demonstrates the framework’s capabilities to combine different stakeholders’ approaches and methods to a joint perspective. Step 1 analyses cross-sectoral pathways, optimizing the technology mix for gas, heat, electricity and mobility. The outputs of Step 1 are used as the main assumptions for both Steps 2 and 4. Step 2.1 details the results of Step1 at a very high geographical resolution. Further analyses performed in Steps 2.2 and 3 consider the impacts on the electricity grid and the gas grid. Meanwhile, Steps 4 and 5 complement the results of Step 1 with an integrated European perspective, accounting for uncertainties, climate change and detailed modelling of electricity flexibilities.

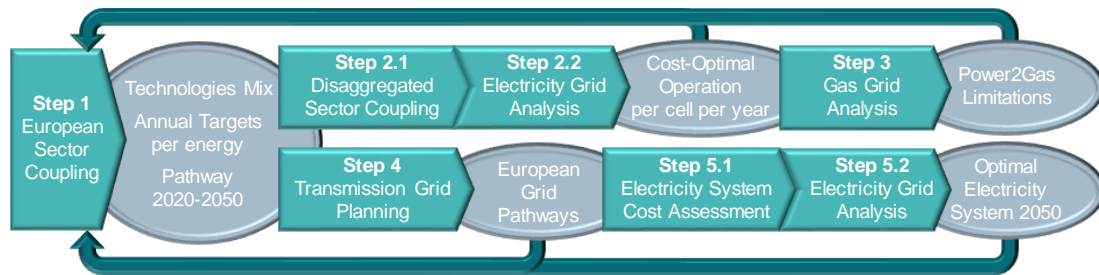


Figure 3. Illustrative workflow demonstrating the plan4res framework’s capabilities to combine different stakeholders’ perspectives to a joint modelling approach applicable to the pan-European Energy System for the period 2020 – 2050. Ellipsoids: outputs; Arrows: models and process steps

MULTIMODAL INVESTMENT MODEL FOR ANALYSIS OF ENERGY SYSTEMS CONSIDERING SECTOR COUPLING

This approach is used in Case Study 1: Step 1 in Figure 3

Specifically, Step 1 involves the application of a multimodal investment and operational model that covers the pathway from 2020 until 2050 with application to the European energy system. To assess the impact of sector coupling on the energy mix an adequate model is needed, which includes all energy-relevant modes (multimodal) of energy into consideration, such as thermal energy for heating, transport energy etc., and focuses not only on electricity. Furthermore, this optimization model should not rely on a given energy mix, a hierarchy of dispatch or a pre-selected set of technologies. Instead, a ‘technology-open’ approach is employed, in which the suitability of technologies for investment and their operation is decided on a cost-optimal way based on the overall economic benefit that each can bring to the system. This way a level-playing field for all technologies is established. In such an optimization framework, investment and unit commitment strategies are optimized together while considering impact from all energy-relevant sectors. This multi-modal investment model (MIM, [10,12-13]) enables the plan4res framework to perform integrated modeling of the European energy system while considering electricity and non-electricity sectors such as the mobility, the heating/cooling, and the fuel/gas sectors.

The MIM is represented in the form of a linear optimization problem in which various technologies and processes are modelled while considering interactions between cross-sector energy flows and for various energy modes (multi-modal). Sets of competing technologies (considering the historically installed base as starting point of the pathway and new technologies potentially to be installed along the pathway) and their necessary support processes are implemented for all energy-relevant sectors. Furthermore, instead of using ‘final energy’ demand as input requirement of a given technology to be met for providing a certain ‘service’, the MIM uses ‘direct used energy’ demand, which is correlated to the actual demand of this ‘service’ to be covered, e.g. the thermal energy that is actually needed for covering the heating needs of a

building, rather than the gas demand for the heating system. The required ‘direct used energy’ can be provided by various technologies. For instance, for the heating demand for a building, examples of corresponding technologies include electrical heaters, gas boilers and district heating, etc. and each linked to a specific type of ‘final energy’ consumption. In this context, the optimizer then “can decide” which of the already installed technologies are most appropriate to be operated and which units should be installed or retired so that the required demand can be met at every hour within a representative year and along the whole pathway. The optimal timing of investment is considered in light of achieving a macro-economic optimum through the minimization of the total investment and operational cost, based on techno-economic parameters such as CAPEX, OPEX, various types of efficiency metrics and CO₂ emission costs related to operation; these latter emissions are capped by considering total annual maximum for CO₂ emission.

Figure 4 presents preliminary results from optimized pathways with application to Germany and France [5,14]. Each national energy system is modeled with the objective of meeting requirements related to their COP21 participation and using projections for primary fuel prices and country-specific developments in population and GDP by [15]. Additionally, country-specific regulations and constraints, including, e.g. France’s commitment to nuclear power [5] and Germany’s decommission plans for coal power plants [4] are taken into consideration.

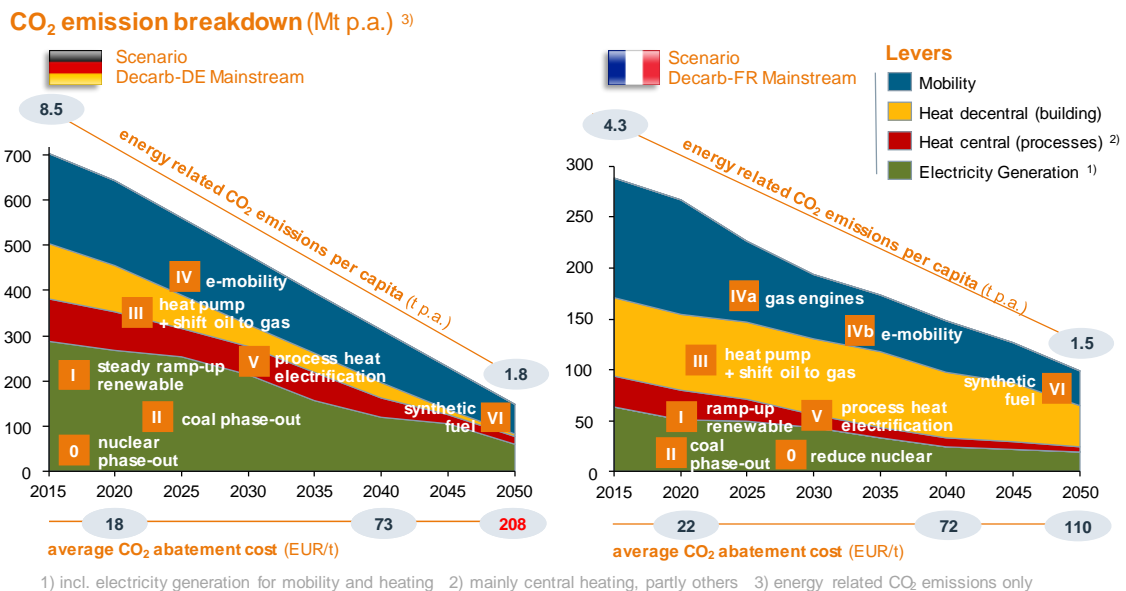


Figure 4 Breakdown of the energy-related CO₂ emissions of the energy systems of France and of Germany following a macro-economic optimal decarbonization pathway. Additionally, cornerstones for decarbonization (0 – VI) and resulting costs for CO₂ abatement (implemented as CO₂ price) are presented along the pathway 2020-2050

Comparing both graphs analogies and differences between France and Germany can be found. Some key findings are presented below:

- Both show early ramp up of RES, such as photovoltaic and wind onshore and wind offshore
- Both show an early loss of fully dispatchable thermal capacity (due to the intended coal phase-out plans and the reduction in nuclear power plant capacity in both countries).
- For both, electrification of heat is implemented early at decentralized consumers, e.g. with installation of heat pumps, and later also at process heating through electrical heaters.
- The transition occurring in road-side traffic exhibits different trends and pathways. Specifically, for France first a shift towards gas-powered internal combustion engines, later followed by a transition to e-mobility is proposed, whereas in Germany the transition leads directly to e-Mobility.
- In 2020, France’s CO₂ emissions are significantly lower than Germany’s; and still are in 2050. Both countries may reach their CO₂ emission targets within the given scenarios, but Germany may require significantly higher CO₂ prices than France and/or extra regulations to achieve its targets.

Note that differences between France and Germany in the last two key findings highlight the need for a joint pan-European energy system strategy.

The MIM approach provides a projection for a future energy system mix through an optimal investment pathway. Thereto the MIM uses aggregated handling of regional clusters and a simplified ‘clustered’ electricity transmission grid (see [16]). Regarding solution times, this model approach enables relatively fast simulation, which allows for conducting sensitivity analyses by testing several scenarios with variations in their input parameters. In addition, in order to get a robust projection of the optimal future energy mix and the required investment pathway, these results are challenged against broader socio-economic constraints. To further increase the robustness of the results, they will be validated at higher geographical resolution, which will require the development of more sophisticated network models. This is performed in the steps 2 and 3 that are presented in the subsequent sections.

DISAGGREGATED SECTOR COUPLING ANALYSIS OF ENERGY SYSTEMS WITH A HIGH SPATIAL, TEMPORAL AND TECHNOLOGICAL DETAIL

This approach is used Case Study 1: Step 2.1 in Figure 3

The goal of this analysis is to determine the cost-optimal operation of the European energy system for specific years within the period 2020-2050, using as inputs the output from Step 1, which includes installed generation capacity for different types of generation units and the amount of heat required to supply thermal demand levels [13,17]. Note that while Step 1 focuses on the entire European energy system, including the heating, transport and electricity sectors, covering the period 2020-2050, Step 2 focuses on the operation of the electricity and heating sectors across single years, while considering a high spatial, temporal and technological detail relevant to each modelled country.

Specifically, the model makes use of aggregation of decentralized generation and storage assets into *energy cells* that cover certain geographical area within countries and that are characterized by electrical and thermal demand at residential, commercial and industrial levels. Also, a wide range of associated technical constraints, such as power plant ramping, minimum up and down times, and the availability of units are considered to provide a detailed representation of the operation of generation assets. This also includes operational constraints for the provision of district heating by conventional power plants. Regarding technologies, the use of power2gas and power2heat technologies, thermal and pumped hydro storage units and a range of thermal and RES technologies is included. The use of a Lagrangian relaxation methodology enables the consideration of a high technological detail, while at the same time performing optimization across a large geographical and temporal scope.”

This approach is used in Case Study 1 and Case Study 3: Step 2.2 and Step 5.2 in Figure 3

Furthermore, power flow and congestion management simulations are conducted as part of this step to analyse the amount of redispatch and renewable curtailment required. Such results are necessary given that the ongoing penetration of wind and solar power capacity leads to the need for network reinforcement to accommodate the resulting increased power flows. Hence, information about the magnitude of power flows can be vital for maintaining the security of supply during system decarbonization.

Note that the consideration of power2gas technologies in the model is especially important as it can contribute to increased system flexibility, which is fundamental to accomplish greater renewable energy integration. Greater flexibility can lead to reduced curtailment of the output from renewable units, which will increase their economic efficiency. Specifically, power2gas units include devices such as electrolyzers that can convert electricity, potentially from RES, into synthetic gas, which can then be stored in the gas grid. Hence, power2gas allows injecting green energy into the natural gas pipeline system, thereby contributing to the decarbonization of the energy system. However, operation of power2gas units is restricted by limitations relevant to the gas grid. A presentation of these limitations and of their consideration in the modelling process is provided in Step 3, presented in the following section.

Similarly, electrification of heating can help in the decarbonization of the energy system. Specifically, power2heat technologies can be useful in times of excess electricity generated by RES, which would otherwise be curtailed, thereby reducing the consumption of fossil fuels in the heating sector.

LIMITATIONS OF POWER2GAS FROM LIMITATIONS OF THE GAS GRID

This approach is used in Case Study 1: Step 3 in Figure 3

The natural gas network is part of the European energy system and serves to transport gas from gas suppliers, such as Norway or Russia, to final consumers, such as industry, distribution service providers for household usage, and gas power plants (GPP). The gas network also serves as a flexibility source for the electricity system. The gas grid interacts with the electricity system by providing gas to GPPs for electricity production and storing and transporting gas from power2gas (P2G) units, i.e., hydrogen and synthetic methane. With the increasing share of RES in the European energy system, the utilization of GPPs becomes more dynamic to balance the electricity demand. This leads to rapid and large-scale fluctuations in the gas demand. On the other hand, P2G units convert surplus electricity produced by RES to hydrogen or synthetic methane. The injection of these into the gas network is limited due to the technical capacity of the gas network as well as restrictions on the gas quality, i.e. the gas composition. Hence, assessment of the requirements related to gas network and storage infrastructure is needed for a comprehensive understanding of the security of the supply of the coupled energy system.

In this context, Step 3 of the plan4res workflow employs a model of the gas grid [18-19], focusing on key regions of the European natural gas transmission. Scenarios of supply and demand at the entries and exits of the network are supplemented by the output from Step 2, including the schedules of power2gas units and GPPs. P2G units receive electricity, mainly generated from RES, and yield hydrogen, thereby representing a supply to the natural gas grid. By contrast, GPP units consume natural gas to produce electricity, leading to natural gas demand. Since the schedules derived in Step 2 do not consider the constraints related to the operation of the gas grid, the gas grid model is used to evaluate whether the capacity of the gas grid is sufficient to cope with these schedules in addition to the demand/supply schedules, e.g., routing gas from Russia, Norway and Algeria through the grid to consumers all over Europe. Results represent additional constraints to the electricity grid operation model in Step 2.

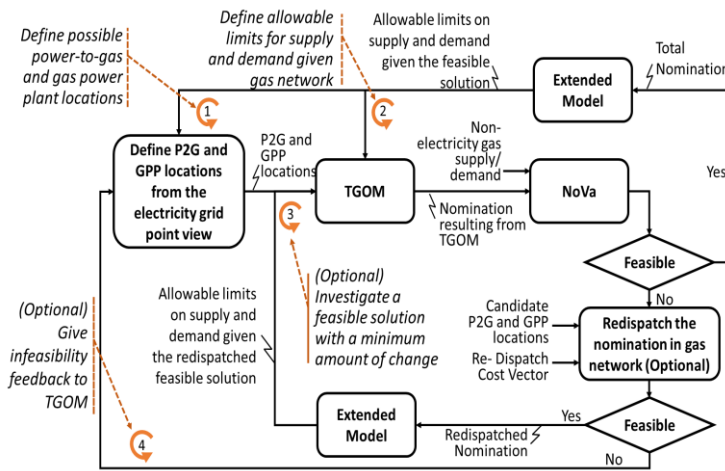


Figure 5. Illustration of the Interconnected Gas and Electricity Model used as part of Step 3.

whether there is feasible operation mode for a given set of supply and demand at the entries and exits of the network, i.e., nomination. Either the problem yields a feasible transport solution for a given nominations or infeasibility related to the constraints imposed by the physical attributes of the given gas network. The output of the NoVa incorporates the gas flow through pipelines, configurations of the active network devices, such as compressors, and the pressure distribution in the network. The reader is referred to [18-22] for a more detailed description of the network elements in gas network optimization models as well for details on the nomination validation problem.

NoVa is performed based on the assumption of a stationary gas network model. Therefore, it does not consider the dynamic effects of gas transport, such as the allowable intra-day flexibilities associated with linepack.

The temporal interconnection between the natural gas network and the electricity grid is not straightforward due to their inherent differences in terms of velocities [18]. The model of the interconnection between the two grids employed in the plan4res workflow is illustrated in Figure 5. Specifically, the transmission grid optimization model (TGOM) representing the electricity grid model of Step 2 provides hourly schedules for the P2G and GPP units to a gas network model that assumes a stationary gas network flow [19]. The model, also referred to as Nomination Validation (NoVa), validates

In the proposed plan4res method, we therefore focus on analysing the allowable transport limits for the gas network considering the maximum and minimum nomination resulting from TGOM. This is conducted as a part of the ‘Extended Model’ that computes the gas supply/demand limits at the entries and exits of the gas network, where schedules are provided by TGOM. These supply and demand limits of gas network based on the initial solution found by NoVa are fed back to TGOM.

If NoVa fails to produce feasible solutions given TGOM’s schedules, we propose to investigate a feasible solution with a minimum amount of change in gas demand/supply provided by TGOM by a gas re-dispatching model. Infeasibility of gas-redispaching model provides feedback to upstream models, which define GPP and P2G facility locations in the first place.

Finally, significant output from P2G units may lead to considerable amount of hydrogen in the natural gas grid. In practice, the level of allowed hydrogen into the gas grid varies among countries. For instance, the UK allows 1% whereas the limit in the Netherlands is 12% [23-24]. Thus, restrictions on the application of P2G are implied by the amount of natural transport.

In order to test our method, a gas network data set, which is comprised of nodes, pipes and compressor stations, is established using available open data sources. Although, the current spatial context of the gas network dataset includes a single country, our data model and analysis methodology are scalable to multi-country-level or EU-level evaluation once the necessary technical data for the gas network is established for the added regions.

STOCHASTIC OPTIMIZATION FOR INVESTMENT PLANNING UNDER LONG-TERM UNCERTAINTY

This approach is used in Case Study 2: Step 4 in Figure 3

Specifically, this approach involves the development and application of a stochastic optimization model, which allows for capturing key sources of long-term uncertainty affecting the European electricity system within the period from 2020 until 2050. Stochastic optimization enables the decision maker/planner to remain flexible and make investment decisions based on how uncertainty resolves. On the contrary, deterministic optimization involves planning under the assumption of perfect information about the future state of the system and restricts the planner to a pre-specified set of developments affecting the electricity system. In this context, planning in a deterministic way can be particularly risky because if the forecast does not materialize then the investments may turn out stranded or underutilized assets.

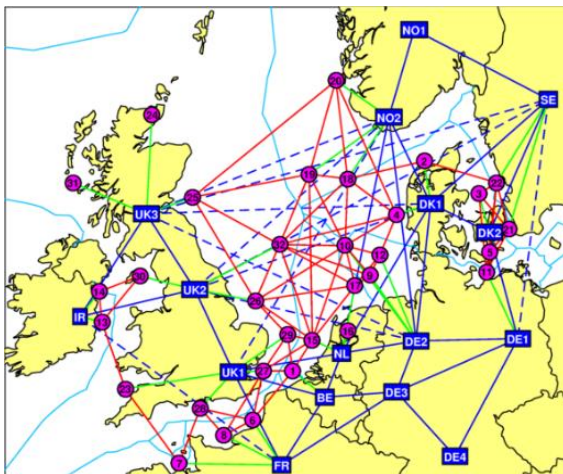


Figure 6. Example of the use of stochastic optimization in deciding optimal investments in the North Sea grid. [26]

Case Study 2 is developed on the premise that uncertainty will be prevalent in the electricity system specifically due to the increasing penetration of RES. A principal related source of uncertainty is the deployment pattern of solar PV and wind generation capacity. Hence, deployment patterns display long-term uncertainty surrounding location, magnitude and timing, which makes network planning a non-straightforward and challenging exercise. The increasing penetration of RES will undoubtedly trigger significant network reinforcement since otherwise there may be violations of voltage as well as thermal network constraints. However, as mentioned above, network reinforcement is no longer straightforward given the significant amount of uncertainty. An example of such eventuality is explained in [25] where solar PV generation is shown to be deployed under uncertainty, since the planner does not know a priori with certainty where and when this solar PV capacity will connect.

Stochastic optimization models involve investment planning by considering numerous scenarios and taking into account the interactions among them in the form of a scenario tree. This form of planning can result in comprehensive investment strategies where investment decisions follow the resolution of

uncertainty and planners have room for alternatives uncertainty resolves unfavorably. Also, with the appropriate use of decomposition methodologies, stochastic optimization can be applied for investment decision making on a national or supranational level, depending on the scope and specific characteristics of the study. For example, [26] involves the application of stochastic optimization in the geographical area of the North Sea examining a range of potential investment alternatives to minimize the total expected system cost (Figure 6).

The importance of stochastic optimization lies in that it has been shown to capture the value of the flexibility that smart technologies hold in dealing with uncertainty as their relatively reduced build times can render the planner capable of adopting a “wait-and-see” approach where high capital investments in line reinforcements can be deferred to the future. From this perspective, [27] shows that first-stage expensive investments are reduced in number, which allows the minimization of the risk of stranded assets given the high amount of uncertainty present in the first stage.

The model used in this study considers investment in conventional assets as well as in smart grid technologies such as energy storage and allows to identify major investments that may be required in different countries and yields the economic value that such new infrastructure can bring to the system.

ASSESSMENT OF THE OVERALL SYSTEM COSTS IN THE CONTEXT OF MASSIVE RES INTEGRATION

This approach is used in Case Study 3: Step 5.1 in Figure 3

Case Study 3 is focused on the pan-European electricity system, including flexibilities provided to the electricity grid by sector-coupling assets. It aims to assess the overall system costs within the context of massive RES integration. Special emphasis is placed on costs that are usually not taken into account in energy models (e.g. costs to maintain frequency stability, costs related to the operation of flexible assets, etc.). In summary, this case study aims to evaluate the costs of RES integration and the value of flexibility, and to highlight the economic impact of climate change on system investment and operation.

The case study will use a tailored version of the plan4res framework that enables modeling key areas of the European electricity system combining investments in generation, transmission, distribution and storage as well as decisions related to system operation such as dispatch of power plants or activation of flexibilities. The case study considers major sources of short-term and long-term uncertainty affecting the energy system, including the electricity demand uncertainty caused by meteorological uncertainties and long-term trends such as the electrification of transport, uncertainty related to renewable sources of generation, water inflows in hydro-reservoirs and unexpected unavailability of assets.

Furthermore, the flexibility associated with generation, storage and consumption is modeled in detail. For instance, a range of constraints are included in the model such as the dynamic operation constraints of power plants (ramping constraints and minimum shut-down duration), dynamic operation of storage (including battery and hydro systems), as well as Demand-Response at various levels (e.g. household load-shifting or load curtailment). Finally, the electricity transmission grid is represented by a ‘cluster’, where a country may be decomposed into a limited number of ‘nodes’ connected with lines of limited transmission capacity, following the approach proposed in [16]. Also, the distribution grid is included as limited capacities (between transmission and distribution) and reinforcement costs for expanding that capacity.

The impact of potential climate change on both generation and demand is accounted for through the use of representative scenarios of different climate change assumptions [28].

To do so, specific electricity-focused models implemented within the plan4res framework are used to simulate the power system operation in 2050. First, the electricity mix (generation storage and demand) per country for 2050, as computed in Step 1, is used as a starting point. It is then complemented by the transmission grid expansion decisions computed in Step 4. While Step 1 includes modeling and optimizing the integrated multi-energy mix over a multi-year horizon, it involves a simplified (linear) modelling of the power system and it is based on a deterministic approach. This first approach is then refined and supplemented in Step 5, thus allowing to assess the crossed effects of flexibilities and constraints and impact of uncertainties, among which the less predictable variable renewable generation, i.e. wind power and PV power. Step 5 involves the following plan4res models [10], implemented within the plan4res modelling system [29]:

- A **power system capacity expansion model (CEM)** which adapts the power mix from Step 1 and the transmission network from Step 4. It will compute an optimal mix of assets including generation plants, storage units, and interconnections capacities, providing the least-cost set of assets, while accounting for the modeled constraints and uncertainties. A stochastic multi-stage mixed-integer non-linear problem will be formulated and solved by approaches combining state-of-the-art decomposition methods [30] and MILP techniques [31].
- A **seasonal storage valuation model (SSV)** which optimizes the mid-term (annual) management of power system assets, mainly hydro systems, but also e. g. mid-term demand-response. This model will provide an accurate account of ‘the value’ that seasonal storage can bring to the system, thus implementing the fact that seasonal storage can be used to store energy over large spans of time and use this “stored” energy when most needed. This problem is solved using Stochastic Dual Dynamic Programming (see [32]). It allows accounting for uncertainties such as water inflows in reservoirs, electricity demand and volatile renewable generation.
- A **European Unit Commitment model (EUC)**, which simulates the short-term operation of the electricity system. It consists of a deterministic optimization problem involving a large number of power plants, load flexibilities and storage devices intending to jointly satisfy a deterministic demand (active power, but also ancillary services) at each node of the network. All assets involve accurate modeling of their constraints (such as ramping, power plant start-up). This model is solved using Lagrangian decomposition approaches and dedicated optimization algorithms for subproblem resolution [30,32].

The consistency of the three above models is guaranteed thanks to the embedded structure of [29]: the CEM model uses the SSV model as a valuation function within the decomposition, and the seasonal storage model itself uses a convexified version of the EUC for the same purpose. The non-convex EUC is then used at the end of the process for simulating the operational process [33].

Within Case Study 3, we will start from the ‘reference scenario’ provided by Step 1 and Step 4 and run the series of models of Step 5 within a sensitivity analysis to assess (Figure 7):

- The impact of different levels of RES integration on the European system costs broken-down by categories: total, generation (investment and operational), transmission and distribution;
- The value of flexibility, i.e., the system cost reduction coming from using the flexibility potentials of the different system assets, which will be computed by simulating different configurations: non-flexible or flexible volatile RES (depending whether they can be curtailed or not, or contributed to ancillary services or not), activation or not of flexibilities from different kinds of storages or demand-response, etc.
- The impact of climate change on system costs, by using time series accounting for different levels of global warming, as implemented in [28]

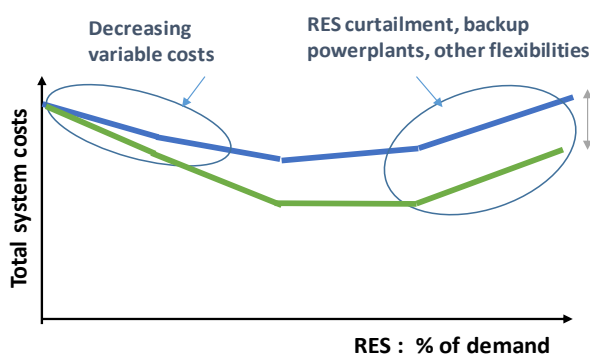


Figure 7
Expected results of Case Study 3: Total electricity system costs according to the rate of RES

SOFTWARE PLATFORM FOR JOINT MODELLING

The plan4res case studies bring together different approaches for modelling the medium to long-term European energy system through the combination and interaction of different models and datasets. Since the case studies are conducted on different computational environments realizing the integration or even interoperation of the components developed by different parties/modelers becomes significantly challenging. Hence, in an attempt to accomplish higher levels of integration, attention has been given

early on to the design of a toolset that will enhance smooth interaction among the models. To this end, this toolset is modular on three levels: data interchange, composition, and computational environment.

The first level, data interchange, ensures that data that are common to multiple models, such as technological attributes of infrastructure, and climate predictions, are possible to use seamlessly through the application of same transformation methods, data aggregation and interpolation techniques. Also, data interchange among models occurs in a well-defined format to avoid ad-hoc data transformations by the different modelers. To this end, a set of Network Common Data Form (netCDF) - based [34] conventions for energy system model data are being developed within the plan4res project. Using the special nested grouping features of netCDF Version 4 allows storing the model data in a form resembling the logical structure of coupled models and also to extract entire submodels' data for reuse in other models. Furthermore, a central private cloud storage service for shared data is used to store all necessary datasets; access restriction methods permit granular control about which datasets are shared and among which set of plan4res partners/modelers.

The second level, model composition, has multiple facets. Firstly, it refers to the structure of the plan4res framework, i.e. the set of the three case studies, and, secondly, to the use of a common database and data format standards based on a shared set of data manipulation tools. The model composition also refers to the use of an optimal set of specialized solution algorithms. For solvers with a programmable API a novel C++-based modelling and solver encapsulation library (SMS++, [29]) is being used. To this aim, a software infrastructure is being built that enables embedding the respective solvers in a common framework. This infrastructure is based on swift-T [35], which is a workflow description language that couples stand-alone applications. Data interchange between tasks can be either through files, but also through dedicated data movement libraries avoiding disc access (UDJ, [29]).

The final level, computational environment, ensures the existence of a common software environment that simplifies maintenance as well as independent software development without the need for alternating between different software environments. To achieve this, a Singularity container [36] has been developed, to allow the software to run reliably across different computational environments. Specifically, using containers allows to deploying applications across operating systems without having to perform separate configurations or builds. Hence, they can be used on a wide variety of systems, from macOS and Windows, to cloud and High-Performance Computing systems.

Summarizing, this section presents the software toolset and framework developed within plan4res to facilitate data exchange and cooperation between stakeholders and ensures that plan4res models and studies can achieve great levels of interoperability which enhances the quality of the results.

CONCLUSION

The current paper describes the modular framework that is developed and used in the context of the plan4res Horizon 2020 project. This framework is a valuable tool to a wide range of stakeholders across electricity and non-electricity sectors, including transmission system operators, distribution system operators, utilities as well as investors, who may tailor it to their specific focus and yield insights about the future energy system.

It consists of deterministic and stochastic optimization models that simulate the operation of the energy system as well as the operation of a range of technologies relevant to the electricity and non-electricity sectors, including energy storage. The modularity of the framework enables detailed modelling of major areas of energy systems, such as generation, storage and transmission and allows us to overcome the complexity of the underlying modelling process. A workflow is presented that demonstrates the interconnection of the modules of the framework and its capabilities for facilitating cooperation.

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