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Modelling and model assessment of grid based Multi-Energy Systems

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ABSTRACT

Strategies to decarbonise energy sectors by substituting fossil fuels with renewable energy sources (RES) pose challenges for today's energy system. RES are mainly decentralised, not always predictable and introduce a high degree of volatility into energy grids. To cope with this challenges, flexible multi-energy-systems (MES) may be beneficial. To assess impacts of high degree of RES on energy grids and derive suitable countermeasures, simulation tools are necessary. In this article we propose a modelling framework suitable to perform a detailed technical assessment of MES. This framework (HyFlow) allows for MES simulation and includes depiction of spatial area and simplification of electricity grids without neglecting its properties. Additionally, we demonstrate the application of HyFlow to assess the impacts of the Austrian energy strategy #mission2030 on the energy grids of an Austrian federal state. We present and analyse two scenarios with various degrees of future generation and demand developments, including sector-coupling technologies, energy storages and electric vehicles. Both scenarios demonstrate that a high degree of renewable electricity generation can be realised with few improvements of the current energy infrastructure. Hybrid technologies such as heat pumps and power-to-gas turned out to be crucial in terms of both, energy efficiency as well as flexibility.

Keywords

Multi-energy-system modelling and simulation;
Energy systems;
Renewable energy integration;
Load flow calculation;

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1. Introduction

In order to meet the binding goals agreed to at the COP 21 in Paris, two major strategies should be implemented: substituting fossil fuels with RES and increasing system efficiency [1]. These strategies present challenges for current energy systems and their operators, since RES are mainly decentralised, not always predictable, and introduce volatility into grids. Therefore, energy systems must be effectively designed and operated to provide temporal and spatial flexibility. MES, which incorporate multiple energy sectors, allow additional flexibility to be used across energy carriers and thus further increase system flexibility. Moreover, these MES can improve overall energy efficiency and allow for seasonal storage of different energy carriers [2].

In general, energy system models which may determine optimal system design- and operation strategies, are tools for suggesting appropriate energy system improvement measures to grid operators or political decision makers [3]. There already exist a number of widely used modelling tools for representing energy grids and infrastructure, but they only consider single-energy carrier networks. However, comprehensive modelling frameworks for MES, which link single-energy networks by using coupling technologies, are to the best of our knowledge not yet available [4], but may further advance the transition to RES.

Making reliable statements with regard to holistic approaches for integrating RES in future energy systems and grid infrastructure requires adequate consideration of network interactions and dependencies by using complex models. [5, 6] In the context of effectively designing and operating grid-based MES, modelling frameworks must take into account multiple aspects of energy

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Abbreviations

BEV	Battery electric vehicle;
DRE	Degree of renewable expansion;
DSS	Degree of self-sufficiency;
ELO	Electricity line overload;
GtPH	Gas-to-power-and-heat;
GtH	Gas-to-heat;
KPI	Key performance indicator
LP	Linear programming;
MES	Multi-energy-system;
MI(N)LP	Mixed-integer-(non)-linear-programming;
PHEV	Plug-in hybrid vehicle;
PtG(H)	Power-to-gas(-and-heat);
PtH	Power-to-heat;
RES	Renewable energy sources;

systems modelling. This includes energy network infrastructures across different energy carriers and flexibility options like storage facilities. Three aspects are relevant for characterizing them:

Firstly (1), the degree of detail determines the model accuracy. A decreased degree of detail reduces model complexity and hence, computational effort. The accuracy specifies how well the original behaviour of the system is preserved. In this work, the cellular approach addresses the issues of detail as a method that supports spatial resolution reduction and thus simplifies physical properties of energy grids. The second aspect (2) is the definition and consideration of boundary conditions which represent all assumptions as well as technical details for all relevant units within the system [1]. Finally, (3), the operation scheduling for flexible system units and utilities must be addressed. This can be done either by mathematical optimisation methods like linear programming or by heuristic approach, considering specific operation algorithms.

As shown in Figure 1, the development of the modelling objective directly influences a model's level of detail (1). In turn, this affects the overall system design (2) and consequently the way the system is operated (3) [4].

2. Motivation

Substituting fossil fuels with RES brings major changes into our energy systems, since RES, firstly introduce high volatility into the grid and, secondly, are spatially spread. This is shown on the example of Austria in Figure 2: Most of Austria's RES potentials are highly volatile solar- and wind-power or moderately volatile hydro-power. The only RES that can be deployed demand-orientated is biomass. This leads to power surpluses – so called negative residual-load (Eq. (1)) during the summer months, mainly occurring in the electrical grid. In contrast, the winter months tend to show temporal shortfalls, while positive residual-loads, according to Eq. (1), occur.

$$P_{\mathrm{Res},i}[t] = P_{Load,i}[t] - P_{Gen,i}[t] \tag{1}$$

Besides their temporal volatility, the Austrian RES-potential is not sufficient to cover the country's primary-energy demand, which accounted to approximately 381 TWh/a [7] in 2017. With RES potentials of around 265 TWh/a [7], a shortfall of around 116 TWh/a [7] is left to be covered. In order to cover this gap, RES imports and/or measures to increase the primary energy efficiency have to be applied in the future.

As we show in Figure 2, besides this general shortfall of RES potentials, there is a strong spatial component as well: Especially the highly industrialised regions of Austria as well as the urban centres are strongly undersupplied in the energy net-balance over a year (indicated in green). Besides the questions related to the RES volatility and the systems energy-efficiency, this leads to

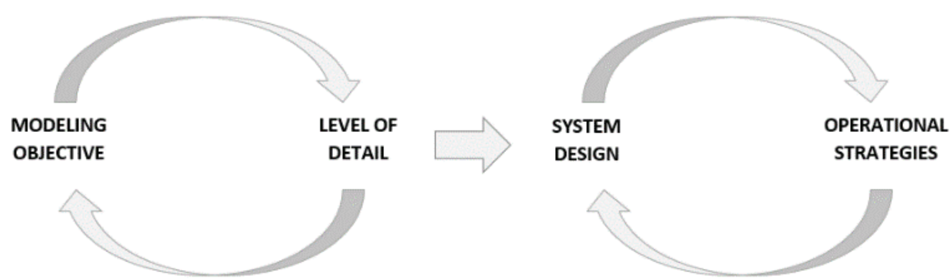

Figure 1: Interactions of the areas in energy system modelling

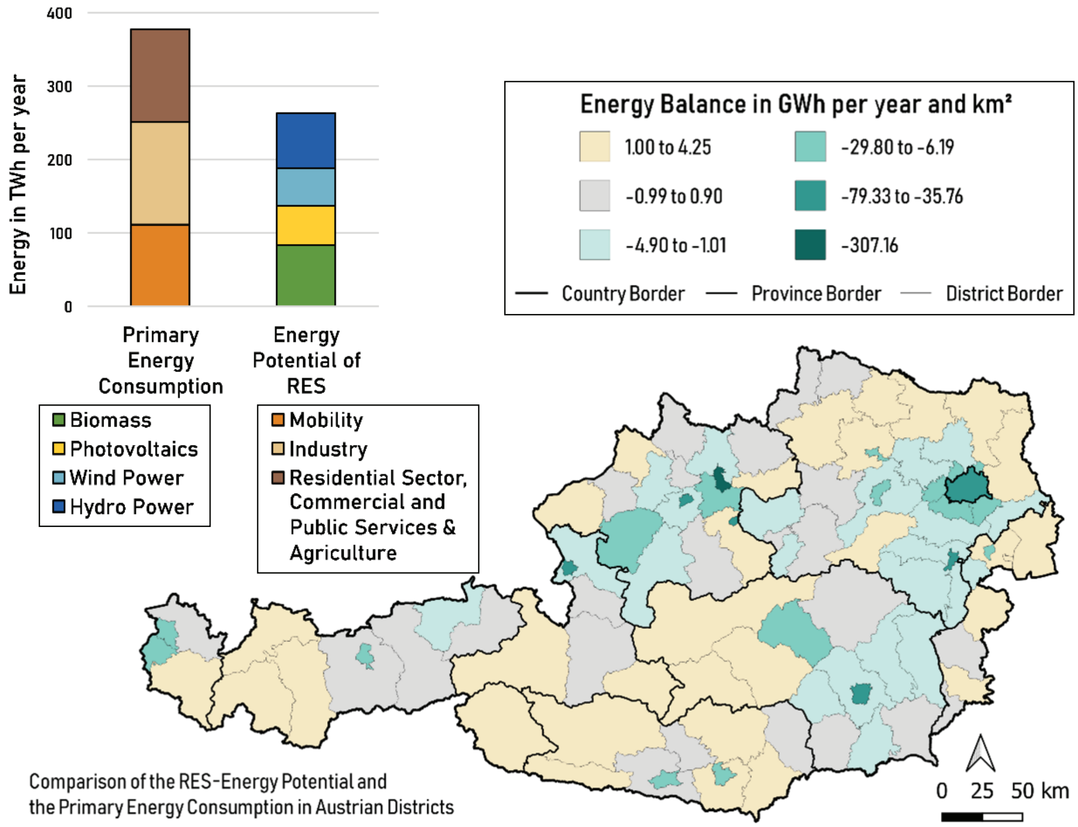

Figure 2: Energy balance in Austrian districts

questions with regard to the energy grids, covering the distances between RES production and demand. Sejkora et al. provide a comprehensive overview on the spatially resolved energy and exergy system of Austria [7].

In order to address the challenges mentioned above, energy system simulations, considering more than one energy carrier, may act as a helpful tool in order to evaluate various solution strategies.

The aim of this work is to show the correlation between the three major aspects of grid based MES as described above. How they are addressed today and how they can be combined in one novel system modelling framework. Further, we show the application and assessment of this modelling framework on a case-study of an Austrian federal state. Therefore, we analyse future impacts of the Austrian Climate and Energy strategy #mission2030, which aims for 100 % renewable electricity production net-balanced over one year, until the year 2030 [8]. We also discuss a solution strategy, in order to enhance the system's primary energy efficiency and to overcome congestions related to the #mission2030 RES expansion.

3. State of research

Current literature in energy system modelling covers distinct perspectives, approaches, and types of models based on different levels of detail. Different types of models (i.e. scenario models, planning models, operating models and optimisations), allow complex energy systems to be considered on several temporal and spatial levels [9]. Either energy-based or power-based perspectives are applied, depending on the type of model. Energy-based perspectives use highly aggregated data such as annual energy demand and supply values, while power-based perspectives calculate models using time-resolved power values [1]. When integrating distributed and volatile RES, it is necessary to ensure the finest possible temporal resolution, since there must be a balance between energy generation and demand at all times [10].

Energy system modelling approaches are either based on one of two principles: top-down or bottom-up, both offering specific advantages as well as limitations [11]. While the top-down-approach pursues macroeconomic considerations – simplifying and aggregating the energy sector by the underlying economic theory – the bottom-up approach presents a techno-economic view. The bottom-up principle includes technological details which are evaluated using an economically-oriented concept corresponding to the investigated technologies, and therefore requires a comprehensive database [10, 11].

Simulation models and optimisation models are the most commonly applied models using a bottom-up approach. Simulation models are used for describing, explaining and predicting the behaviour of energy systems. Attaining a specific goal, such as optimal unit scheduling or optimal dispatch, requires the application of optimisation models in order to define an optimal set of technology options. This goal should be achieved by minimising operating costs under certain constraints, while at the same time, energy quantity and prices should remain unchanged [11].

The model formulation requires mathematical equations describing the energy system appropriately. Linear programming (LP), mixed-integer linear programming (MILP) and mixed-integer non-linear programming (MINLP) are most commonly used in this context. Almost all optimisation models used in energy system planning are LP models as they are fully linearised. They are therefore easy to use and deliver fast results. For the same reason, they tend to deviate for non-linear conditions [9]. MILP models extend LP models as they offer greater detail in terms of technical properties. MINLP models tend to better approximate the real energy system as they also map non-linear conditions, but they require more calculation time [9, 12].

The models can also be categorised according to their modelling scope. While planning models are used to assess long-term developments of energy-systems, operating models are used to assess the reliability of scenarios in terms of their operating conditions. They differ mainly with regards to the time horizon: planning models must consider long periods of time, whereas operating models range from one day to one year. Additionally, planning models usually use an energy-based-perspective, while operational models use power-based-perspectives [1].

For this work, MES operational models turn out to be relevant. To gain an overview about existing models, we compared listings from various databases [13–15]. Following filter criteria were applied on all previously described MES listings:

- MES must be open source and accessible to enable further development.
- Energy carriers electricity, gas and heat must be included to depict MES.
- MES must be an operational model, that allows scenario based simulations.

Three open-source MES modelling tools Calliope, OEMOF and URBS could be identified meeting the criteria mentioned above. However, they focus on economic tasks such as optimal dispatch based on minimal costs not on technical questions.

Commercial software such as DIgSilent PowerFactory, NEPLAN and PSS Sincal provide highly accurate grid depiction and load flow calculation. However, they don't provide any interconnection between different energy carriers, therefore they are unsuitable for the assessment of MES [16–18].

In comparison to MES planning tools like EnergyPLAN or TIMES, HyFlow aims not to determine an optimised MES. The main motivation for HyFlow is to assess technical infrastructure impacts by scenario based changes of consumer and producer behaviour as well as impacts of sector coupling and storage technologies. Therefore, MES planning tools such as EnergyPLAN or TIMES can be a valuable supplement for HyFlow, providing input data for further detailed technical assessment [19, 20].

To conclude, the literature analysis shows that multiple MES assessment tools are available. However, as shown in Figure 3 existing grid based MES models cannot be used as scenario based operational models, commercial software cannot implement sector-coupling technologies and future MES development assessment tools lag detailed energy grid depiction.

Our self-developed hybrid MES simulation tool HyFlow aims to address before mentioned issues: a scenario based operational model with implementable sector-coupling and storage technologies in combination with detailed energy grid depiction.

4. Methodology

The following section explains the methodology for each relevant part of MES modelling. The first subsection, "Cellular approach – level of detail", explains the relevance of degree of detail when using the cellular approach which supports spatial-resolution reduction. Based on the cellular approach, network design of energy networks is described in the second subsection "Energy network modelling". In subchapter three "MES modelling and simulation tool" we describe how we apply before mentioned methodologies in the mentioned grid-based MES modelling framework HyFlow.

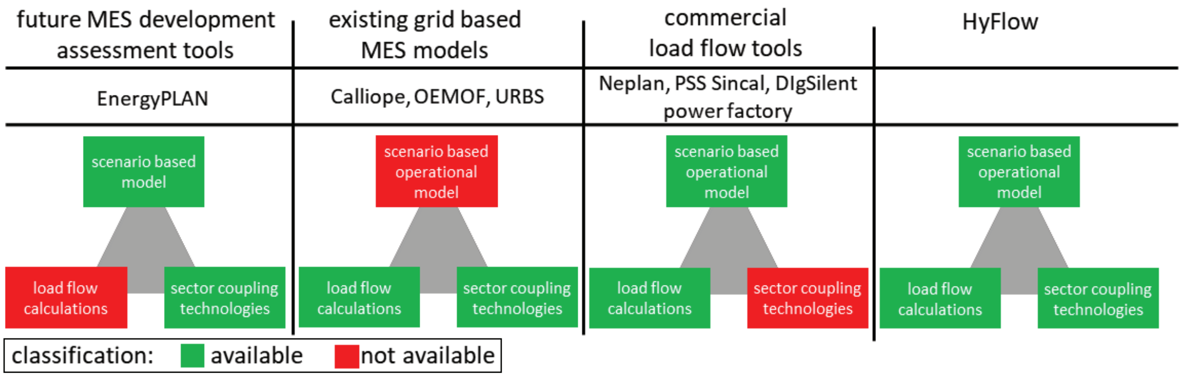

Figure 3: Research gap between commercial software and existing grid-based MES models.

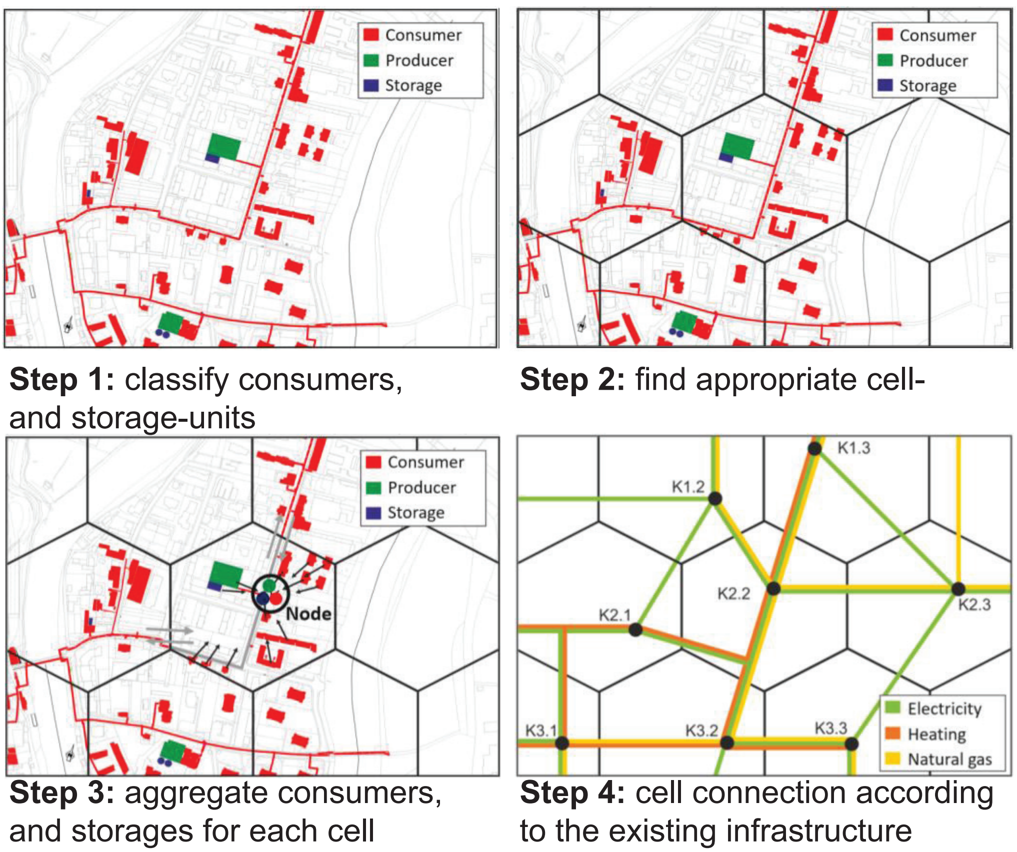

Figure 4: Visualisation of process steps within the cellular approach

4.1 Cellular approach – level of detail

The main objective of this approach is to balance supply and demand at the lowest possible level to prevent high load flows over network connections. The cellular approach also is a means of aggregating users (e.g. consumers, producers and storages) in nodes to reduce computational time. Additionally, aggregating the users within one cell allows for standard load profiles [21] and synthetic load profiles [22] to be used, even if the data of the modelled region is incomplete.

The cellular approach is designed to be as modular and generic as possible. The process of applying the cellular approach is visualised in Figure 4. All energy consumers, generation and storage units are aggregated to a single node within a defined cell or system boundary. This procedure is followed for each energy carrier.

It is important to choose cells according to the geographical distribution of users, the number of aggregated users, and the grid routes. A more detailed explanation on cell design and recommendations within the cellular approach can be found in [23, 24].

The energy generation $P_{Gen,i}(t)$ and the demand $P_{Load,i}(t)$ for each time-step and each energy carrier are combined in the residual load $P_{Res,i}(t)$ as defined in Eq. (1). The resulting nodes containing the residual loads of each cell are now linked via intercellular connections, if a real grid connection exists between the cells. Importantly, the interconnecting lines are modelled to fit the original grid as accurately as possible. This includes network reduction measures such as appropriate compensation lines instead of multiple lines from one cell to another.

Cells of the same level (e.g. households) can be further aggregated to a superior cell level (e.g. city quarter) in order to allow the spatial flexibility needed. Cells can represent a wide variety of sizes. They may be city quarters as depicted in Figure 4, but may also represent a single household or any other unit. The size of the smallest cell level is important because intracellular load flows within the smallest cell levels are neglected.

4.2 Energy network modelling

Electrical grid: Currently, the greatest challenge when implementing volatile renewables into an energy system, is the lack of transport and storage possibilities within the electrical grid [25]. Therefore, electric networks need to be accurately modelled in order to make reliable statements regarding infrastructural planning of future network structures. When modelling electrical grids, DC- and AC-load flow models are used. While DC-models are simplified, or rather linearised, by taking into account only active power flows, AC-models also consider reactive power flows. This allows for electrical grid transmission characteristics to be described more precisely [26]. Reactive power is required for building up electromagnetic fields which facilitate energy transmission. Analysing reactive power in electrical networks allows additional network aspects to be assessed. This includes overloads of network elements, voltage stability, network losses, network capacity calculations and determining the grids behaviour in case of failure. Network elements, non-linear loads, fluctuating power consumption and asymmetrical network loadings also introduce reactive power into the grid. Additionally, reactive power conditions within network structures depend on voltage levels and degrees of loading [27].

Modelling reactive power flows in aggregated network models according to the cellular approach is therefore a complex process. Since each cell is represented by a single node, changes in the network structure occur. This requires the implementation of compensation elements. Therefore, we apply serial RLC-elements and adapt with them the changed nodal conditions after aggregation in order to correctly model active and reactive power flows within the connecting lines between cells. This process and the structure of one compensation element are shown in Figure 5.

These serial RLC-elements are parameterised using electrical line parameters of the neglected lines (dotted lines in Figure 5, left) within one cell. Thereby, these elements represent complex electrical impedances allowing variable active and reactive power correction with changing operating states of the network. The active and reactive power produced by them compen-

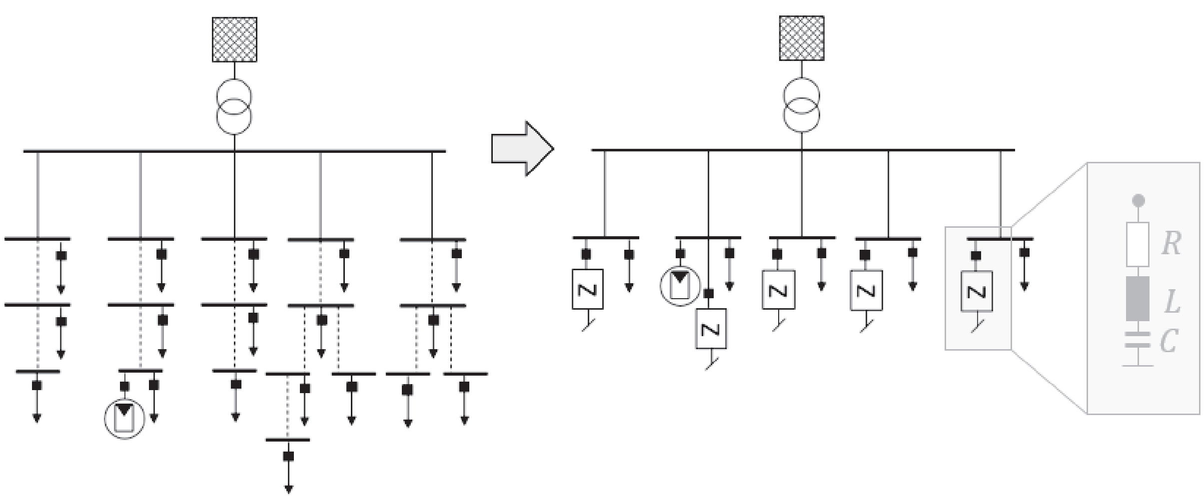

Figure 5: Grid reduction and compensation of losses by means of RLC-elements

sates for the neglected line losses and, therefore, also corrects the overall network losses, the load flow via the slack-node as well as the load flows between the cells. Traupmann et al. [28] give a detailed explanation of grid reduction and compensation procedure.

Pipeline grids – heat and gas grid: Enabling cross energy carrier load flows in MES, mainly for extending storage and transport possibilities available for covering both, positive and negative electrical residual loads, requires an optimised and coordinated use of existing infrastructures. Therefore, pipeline grids for heat and gas also need to be considered using correspondingly created models.

Pipeline network load flow calculations can be used to evaluate various gas- and heat network parameters such as average flow rates V, pressure drops Δp, pressure distributions and temperatures. The mathematical formulation of the load flow equations for pipeline networks is significantly different compared to the electrical grid. The correlation describing the behaviour of pipeline grids shows quadratic dependency according to Darcy's law - Eq. (4), taking into account the Darcy friction factor λ, the pipe length l and diameter d as well as the fluid density ρ. [29] The following equations Eq. (2) to (4) show similarities between both electrical and pipeline networks:

$$\Delta p \triangleq \Delta U \tag{2}$$

$$\dot{V} \triangleq I \tag{3}$$

$$\Delta U = R.1 \quad \triangleq \quad \Delta\, p \frac{\lambda \cdot l \cdot \rho \cdot 8}{d^5 \cdot \pi^2} \cdot \dot{V}^2 \tag{4}$$

Practical pipeline models use a static approach that solves the quadratic Darcy equation by using linearization methods or non-linear solution methods [30, 31]. Compared to electrical networks, additional input variables are necessary to characterise a pipeline network. For example, input variables such as medium density, medium and ambient temperatures, pipe diameter, length, roughness, and thermal conductivity are considered. In district heating networks heat losses occur. They are decoupled from average flow rates and the corresponding pressure drop. Therefore, they only depend on variable fluid and ambient temperatures [32]. Pressure losses are considered in both heat and gas networks. Heat losses over a pipe section are based on different inlet and calculated outlet temperature which considers pipe parameters such as thermal conductivity, pipe length and diameter. Boeckl et al. [33] give a detailed explanation of the grid procedure, depicted here briefly.

4.3 MES modelling and simulation

The temporal and spatial challenges, explained in the previous sections, require for tools allowing the consideration of various RES expansion scenarios, the determination of resulting grid constrains, as well as for the design of flexibility options needed for their mitigation. In this work we introduce a MES modelling framework - HyFlow - that addresses these points. In order to allow the consideration of a broad range of energy system case-studies, HyFlow works on three cell levels with a different spatial depth of detail, individually selectable by the user. Level 1 cells can for instance represent low-voltage grid areas and level 2 cells the medium voltage area supplying them. Consequently, in this example level 3 would be the high-voltage grid area, supplying the lower grid-levels. A level 3 cell is also concerned with the energy exchange to the superior energy system. So called slack-nodes allow energy to be transferred between network levels. This concept is shown in Figure 6.

In addition to the network structure of all considered energy carriers, information regarding physical network properties, timely resolved customer demands, timely resolved generation profiles as well as parameters for describing flexibility options like storages and sector-coupling technologies (= hybrid element) must be defined. Demand and generation data are represented by using residual loads according to Eq. (1). Flexibility options are integrated via technology-independent parameters in order to allow the implementation of various technologies, as shown in Table 1.

In HyFlow, for the operation of flexibility options we apply a rule-based approach instead of mathematical optimisation. Thereby we distinguish between cell- and overall system serving operation. The cell serving

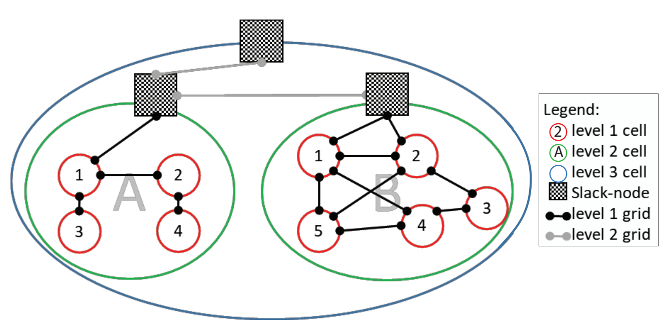

Figure 6: Various network levels in combination with the cellular approach

approach aims to reduce the residual load of the corresponding level 1 cell to a maximum extent. The overall system serving approach aims to reduce the electrical residual load of the highest level being considered (level 3 cell). The electrical residual load is chosen since electricity grids are considered as most critical of congestions. An overview about which hybrid elements are implementable in HyFlow is given in Figure 7. Four main categories (GtPH, PtGH, PtH, GtH) of hybrid elements are shown, each category considering various subtypes of hybrid element technologies.

The computation-steps for considering the interactions between the calculation of multi energy carrier load flows and the operation of cell- and system serving flexibility options, are shown in Figure 8 for one time-step. Dark arrows indicate the first computation loop, whereas light arrows indicate an additional calculation loop in case system serving hybrid elements are activated.

In the first step, each level 1 cell and its corresponding flexibility options, both, in cell as well as system serving operation mode, are fully used to minimise the residual load of the corresponding level 1 cell. Any energy storage capacity of system serving elements, still available after balancing cell-level 1, is used as described in step 3 and 4 to minimise the system's residual load.

After energy storages were used to minimise a level 1 cell's residual load, cell-serving hybrid elements such as PtH, GtPH and GtH are used. The detailed mode of operation for each hybrid element depends on various factors such as storage levels and residual loads. For example, if a PtH hybrid element is to be used, the electrical residual load of the corresponding level 1 cell must be negative (generation), the heat residual load positive (demand) and/or free storage capacity in thermal energy storages available. In this case, the generated electricity would be used to produce heat, and if heat demand is met and there is still electricity left, it would be used to

Table 1: Necessary data for storage and hybrid elements

Storage	Hybrid element
storage capacity	power
charge / discharge power	conversion efficiency for each
charge / discharge efficiency	energy carrier
self-discharge	ramp rate up & down
operation strategy	operation strategy

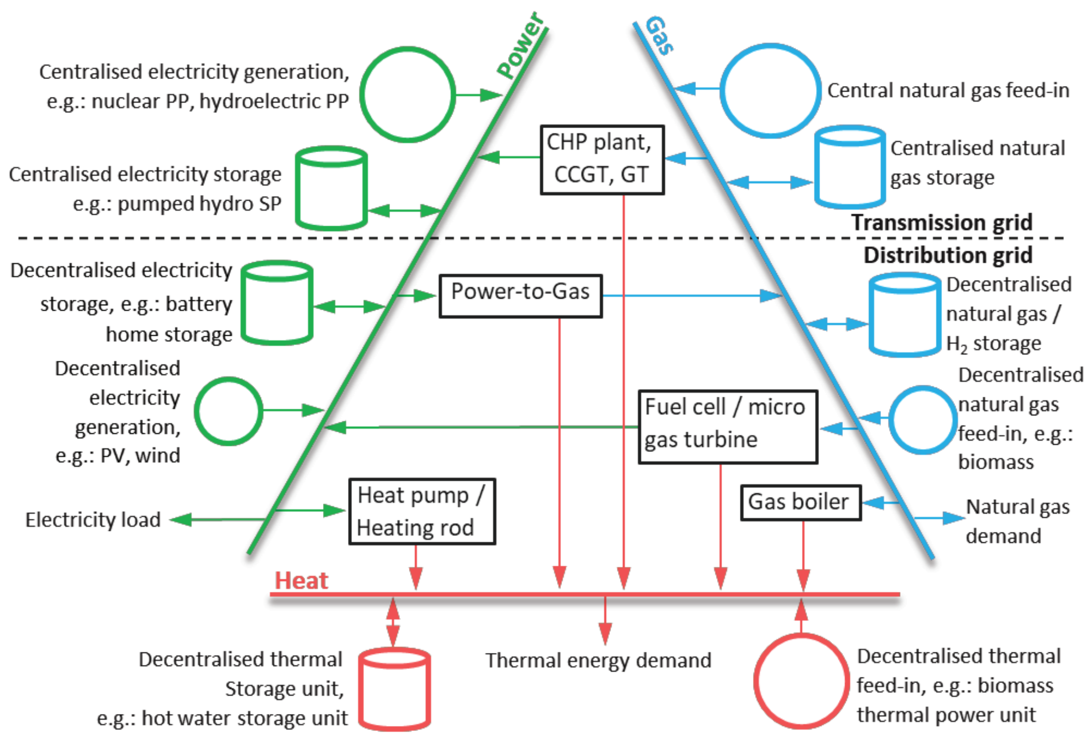

Figure 7: Cross energy carrier and storage flexibility options in HyFlow

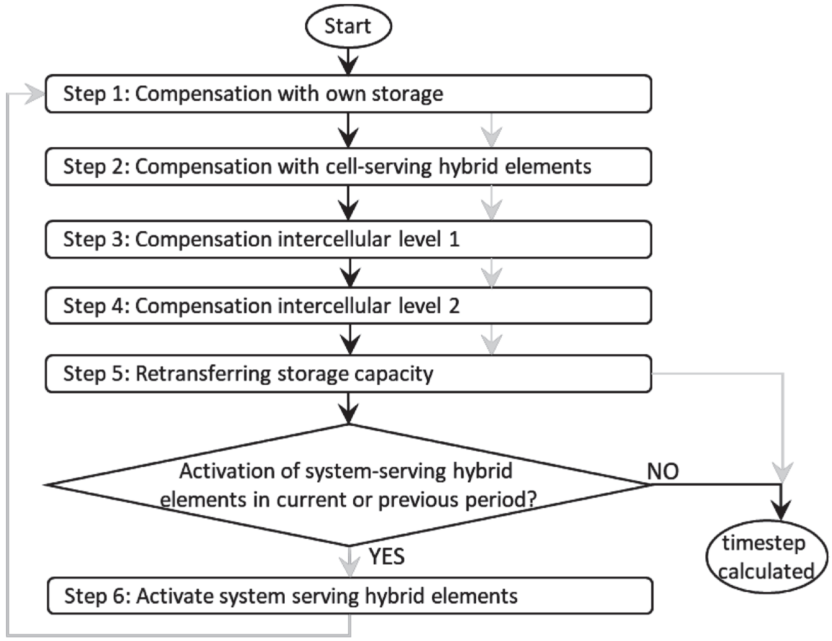

Figure 8: Calculation steps in *HyFlow*

charge the thermal energy storage, if the maximum power of the PtH hybrid element is not exceeded.

In step three, each level 2 cell, with its corresponding and already balanced level 1 cells, is balanced. In Figure 6 two level 2 cells, A and B, and their four respectively five corresponding level 1 cells are displayed. To calculate load flows within each level 2 cell, load flow calculations (see section 4.2) are performed. Leftover capacities from system serving storages located in cell-level 1 are used in order to minimise residual loads of a single level 2 cell by transferring energy to or from energy storages in the corresponding level 1 cells containing the storages. The remaining residual load is balanced via slack node.

Step four is similar to previously described step three. Just as in step three, load flow calculations are carried out in order to calculate load flows between level 2 cells. The remaining residual loads are balanced via slack node, per definition to or from outside the systems boundaries. Since storages are defined in level 1 cells only, virtual storage capacities between level 2 cells are used. The virtual storage capacity of each level 2 cell is the sum of all system serving storage capacities of the corresponding level 1 cells. If any system serving storages were used in step 4, the virtual storages' charging levels change and have to be retransferred to the corresponding level 1 cells of each level 2 cell. This procedure is carried out in step 5, using an iterative process. However, the iterative process affects the residual loads of level 1 cells, where the system serving storage is physically located. Therefore, load flow calculations, similar to step 3 and 4 have to be executed again, to recalculate load flows and grid losses between both level 1 and level 2 cells.

Afterwards, the need for usage of system serving hybrid elements is evaluated. In case hybrid elements were active in the previous time-step or used in the current time-step, calculation steps one to five have to be repeated (see Figure 8 – grey arrows). The usage of system serving hybrid elements depends on the electricity residual load. In case of a negative electricity residual load, excess power is used within the system by system serving hybrid elements such as PtH and PtGH. If the electricity residual load is positive, additional electricity is generated inside the system. Prerequisite conditions for both cases are the availability of suitable hybrid elements within the system.

As a result, time resolved residual loads for each energy carrier as well as the usage of storages and hybrid elements are displayed for all calculated time-steps. Further information such as line loads, node voltage, pressure or temperature levels as well as information regarding the usage of each energy storage and hybrid element can be assessed.

5. Model assessment on the case-study of an Austrian federal state's MES

In order to demonstrate and assess the capabilities of HyFlow, the effects of the national Austrian climate and energy strategy #mission2030 on federal state level, are examined. With regards to the expansion of RES, the specific energy policy of the considered federal state doesn't allow additional wind power [34–36]. Therefore, hydroelectric, photovoltaic and biomass expansion are the only RES options to be exploited in the future. In Table 2 technical- as well as exploitable renewable electricity potentials for the federal state are displayed.

To take possible development-pathways of the federal state's energy consumption until the year 2030 into consideration, two different scenarios are presented:

Scenario 1 represents the climate and energy policy based scenario, where total energy demand is expected to be stable throughout the year 2030. Renewable electricity potentials are almost exploited up to a degree to meet the expected demand. In comparison to the climate and energy policy scenario a further, more ambitious scenario 2 is presented.

In the second scenario the total energy demand is expected to decline, whereas the renewable technical potentials are fully exploited. Scenario 2 aims to show upcoming challenges from an increase of volatile electricity producers, especially in the federal state's electricity grid. Both scenarios were developed in cooperation with the federal state's regional utility, providing both, energy residual load and grid data. Based on grid data the federal state's energy network is depicted in 96 energy cells, with distinctive residual load characteristics.

5.1 Scenario 1: Climate & Energy Strategy Scenario

In the study "Empowering Austria" from Oesterreichs Energie [41], several studies regarding future energy consumption development in Austria are compared. The final energy demand forecasted for the year 2030 ranges from a decrease of minus 9,5 to plus 1,7 percent, based on the final energy demand of year 2012. For this scenario a conservative approach is selected, therefore the total final energy demand until the year 2030 is expected to be stable. Table 3 shows the expected final energy demand in the year 2030. Considering the trend of further electrification and population growth, an increase in electricity demand and mobility can be expected. In the scenario, those increases are countered with savings in heat and natural gas sector.

To cope with an increasing electricity demand and to fulfil the federal state's energy strategy for 2030, RES have to be expanded up to a level to produce 14.874 GWh of electricity per year [42]. Figure 9 shows the amounts of each renewable source to be expanded until the year 2030. It can be seen that hydropower and biomass potentials have almost been fully exploited today, therefore photovoltaic is the only real option to be expanded.

Scenario 1 is further divided into two cases to examine the influence of technologies such as heat pumps, electric vehicles, home electricity battery storage and a central power-to-gas facility on the federal states energy grids. In the base-case none of the mentioned technolo-

Table 2: Technical and exploitable renewable potential

Source	Production 2017 [GWh]	Technical potential [GWh]	Exploitable potential [GWh]
Hydropower	9.909 [37]	11.158 [37, 38]	10.784 [38]
Biomass	963 [37]	2.470 [39]	1.370 [40]
Wind	90 [37]	812 [39]	90 [37]
Photovoltaic	252 [37]	3.344 [39]	---

Table 3: Demand development in climate & energy strategy scenario

Sector	Final energy demand 2017 [GWh]	Final energy demand 2030 [GWh]
Electricity	14.604 [37]	15.334
Natural gas	14.404 [37]	12.734
Heat	21.259 [37]	20.621
Mobility	17.921 [37]	18.548

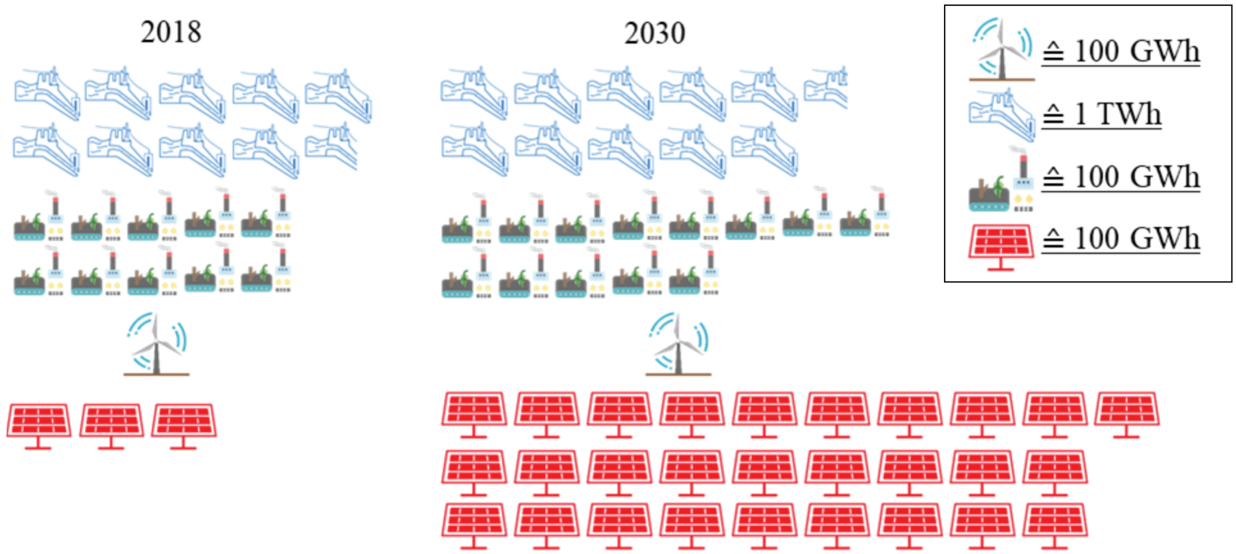

Figure 9: Expansion of renewable generation to fulfil energy strategy goal

gies is implemented. In the advanced case, all technologies mentioned above are implemented. The degree of implementation of each technology follows the assumptions explained in the following:

- We replace natural gas for heating purpose by heat pumps in combination with thermal storages. To determine the spatially resolved consumption of natural gas for heating purpose, the total natural gas consumption is separated in natural gas demand for heating and industrial process demand. The individual heating- and industrial process demand for each cell is calculated considering available consumption data from both, utilities and industrial companies as well as from the study Renewables4Industries [39].
- A study from Pötscher [44] expects all newly registered vehicles in the year 2030 to be a mixture of 70% plug-in and 30% battery electric vehicles (PHEV, BEV) . The Austrian Automobile Association ÖAMTC expects the share of newly registered petrol or diesel only powered vehicles to be almost zero in the year 2030. The ramp-up curve of BEV in the ÖAMTC study is almost linear from today's market share until the year 2030, therefore a linear ramp up curve is selected for this work [45]. Based on the trend of past vehicle registration statistics, the annual vehicle registration number is assumed to be stable with 60.000 vehicles per year until the year 2030 [46]. The described statistics and ramp-up curve result in 130.000 BEV and 302.000 PHEV in the federal state in the year 2030. The charging behaviour of two PHEV is assumed to be like one BEV, therefore a total number of 281.000 electric vehicles is considered in the scenarios with a time resolved arrival characteristic from the project Move2grid [47]. The number of electric vehicles per cell is calculated based on the share of population per cell, compared to the federal state's total population.
- For every household we apply a home electricity battery storage, with a storage capacity of 10 kWh and charge / discharge power of 4,8 kW.
- We implement a central PtG facility in the centre of the federal state with unlimited capacity to convert excess electricity generation into natural gas instead of exporting. The centralised location was selected according to the existing infrastructure of high pressure natural gas as well as the high voltage electricity transmission grid.

5.2 Scenario 2: Ambitious Scenario

This scenario aims to demonstrate the occurring effects if renewables are exploited up to their exploitable potential (see Table 2). This results in a significant increase of volatile renewable electricity generation. The final energy demand in scenario 2 is reduced by 7,5 percent in each sector, compared to scenario 1, resulting in a final energy consumption as shown in Table 4. Scenario 2 is divided in a base- and advanced case, analogously to scenario 1.

6 Results of federal state's scenarios

In this chapter results from both scenarios are presented, discussed and compared. Additionally, we compare our results with other research in this field.

6.1 Scenario 1: Climate & Energy Strategy Scenario

Figure 10 shows the electricity demand and renewable generation in a summer- and a winter week for scenario 1 in the year 2030. Negative electricity residual loads can appear even during winter months, rising significantly in both, count and excess during summer months. The overproduction of electricity in summer reaches similar levels compared to the electricity demand.

Table 4: Demand development in ambitious scenario

Sector	Final energy 2017 [GWh]	Final energy 2030 [GWh]
Electricity	14.604 [37]	14.239
Natural gas	14.404 [37]	11.728
Heat	21.259 [37]	19.027
Mobility	17.921 [37]	17.204

A comparison of electricity load flows in the federal state's transmission grid (transmission grid voltage: 110 kV) to or from the superior electricity system grid for the base- and advanced case scenario is displayed in Figure 11 and Figure 12. In the advanced case, far less electricity is exported over the system boundaries, compared to the base case. Instead of being exported, excess electricity is used within the system, feeding battery storages, heat pumps and a central PtG facility. Especially during days with high photovoltaic generation, the PtG facility is able to supply the federal state's whole natural gas demand. From April until October electricity imports are hardly necessary, compared to winter months with excessive electricity imports.

The federal state's primary energy demand can be reduced from 37.600 GWh by approximately 15 % in the base case to 32.100 GWh in the advanced case. Electric vehicles and sector-coupling technologies such as PtH and PtG are the main drivers for primary energy savings.

By examining the electricity grid in detail, line-overloads can be analysed. In the base case scenario, the total overload time is 3.500 hours (relative overload time: 0,41 %), whereas in the advanced case, a total overload time of 12.800 hours (relative overload time: 1,49 %) occurs across the federal state's electricity

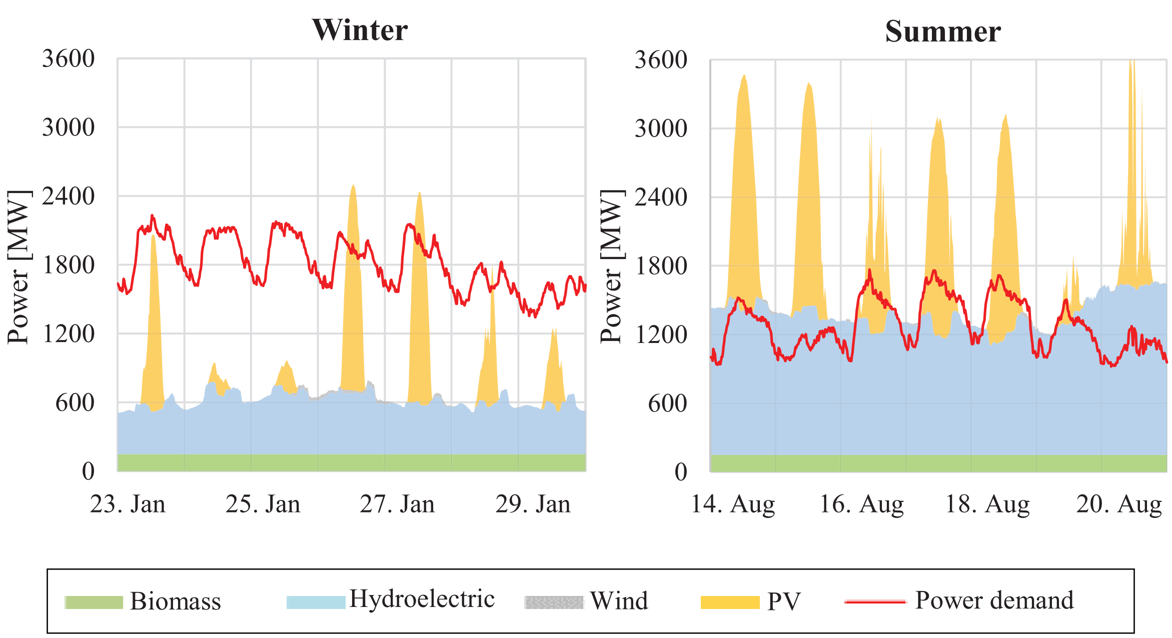

Figure 10: Scenario 1 - Electricity generation and demand in summer and winter

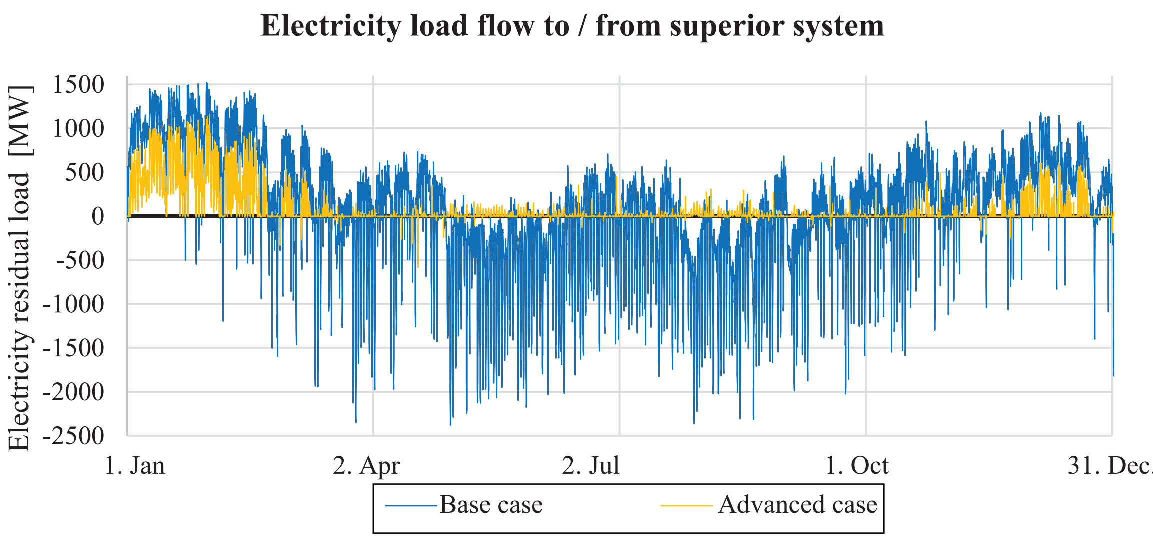

Figure 11: Comparison of electricity load flow in base and advanced case

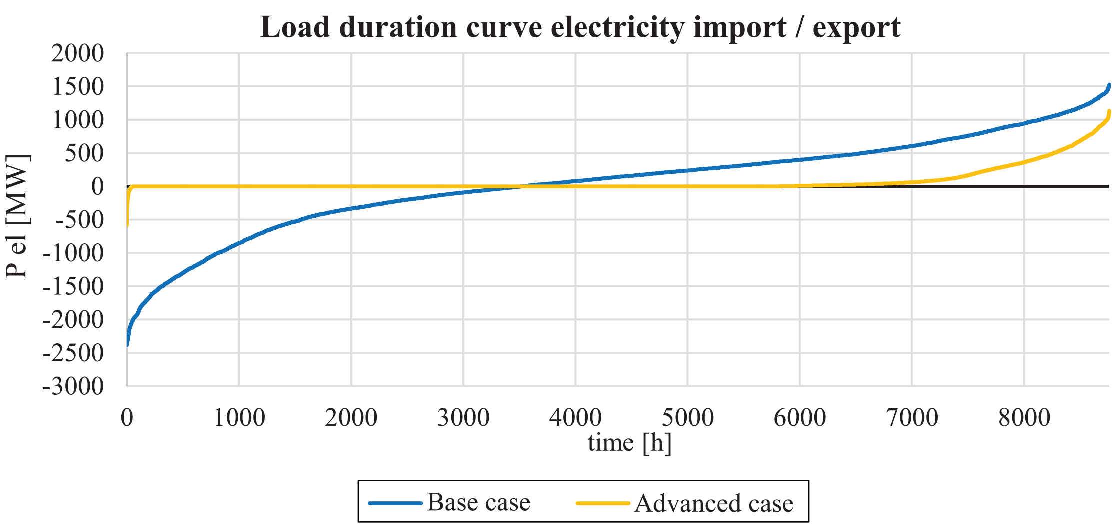

Figure 12: Comparison of load duration in base and advanced case

grid. The electricity grid examination shows that many overloads occur due to operation of the central PtG facility. Since no grid expansion is considered, the number of overload hours can be reduced significantly by expanding certain electricity lines, especially around the central PtG facility or considering several decentralised PtG facilities.

6.2 Scenario 2: Ambitious Scenario

Compared to the previously presented scenario 1, the federal state's electricity demand decreases slightly, whereas renewable generation increases significantly. This results in even more excess electricity generation, reaching up to more than twice the federal state's peak electricity demand, shown in Figure 13.

Due to the higher overproduction of electricity in scenario 2 compared to scenario 1, the central PtG facility converts even more excess electricity into natural gas. The increase in electricity to natural gas conversion leads to occasionally negative residual loads in the federal state's natural gas grid during summer. Negative natural gas residual loads can be stored temporary in the federal state's natural gas storages. The amount of natural gas being imported can be reduced by about 25 percent in the base case and 45 percent in the advanced case compared to the year 2017.

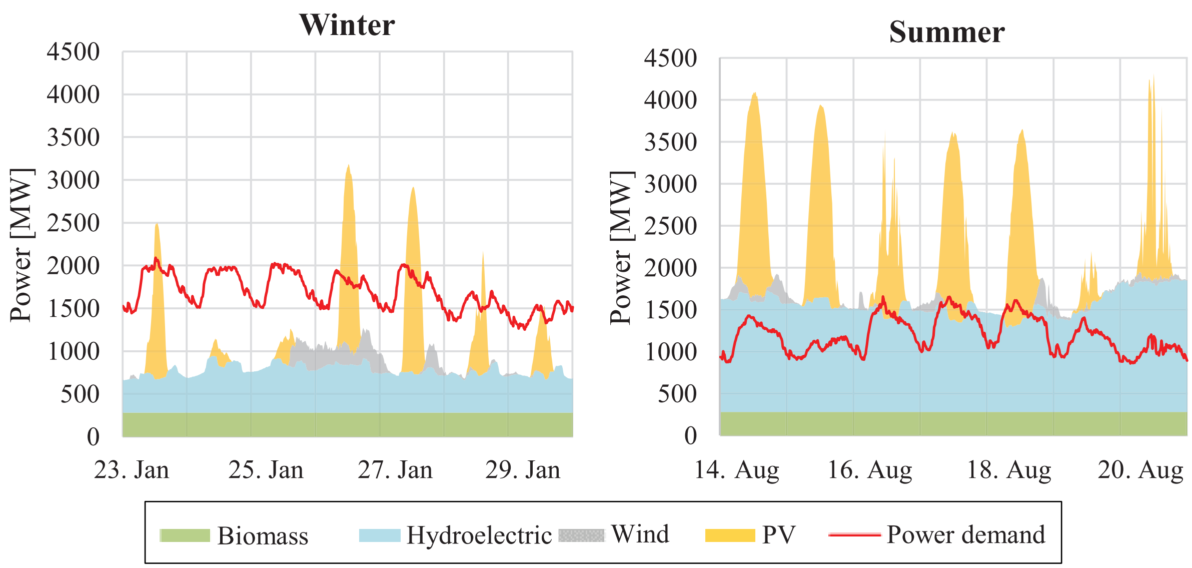

Figure 13: Scenario 2 - Electricity generation and demand in summer and winter

Heat pumps in combination with thermal storages can significantly reduce negative electricity residual loads during winter months. However, heat demand is low during summer months therefore, heat pumps hardly contribute to residual load reduction during summer. The federal state's primary energy demand can be reduced from 35.900 GWh by approximately 18 percent in the base case to 29.400 GWh in the advanced case.

In the base case scenario, the total overload time is 10.696 hours (relative overload time: 1,25 %), whereas in the advanced case a total overload time of 33.496 hours (relative overload time: 3,90 %) occurs across the federal state's electricity grid. Like in scenario 1, no line expansion has been considered and overloads appear mainly in certain grid sections close to the central PtG facility.

6.3 Comparison and discussion of scenarios

The following Table 5 displays key performance indicators (KPI) for both scenarios such as degree of self-sufficiency (DSS), share of RES in the electricity sector, degree of renewable expansion (DRE), relative electricity line overload (ELO) time and primary energy demand.

A high RES penetration correlates positively with DSS, ELO and negatively with primary energy demand. For both scenarios, the advanced case is capable of increasing electricity DSS compared to base case. Comparing relative ELO in each sub scenario a high degree of RES seems unfavourable in terms of relative ELO. However, a detailed overload analysis has shown that in both advanced cases line overloads occur mainly on a few transmission grid sections around the PtG facility. If these particular grid sections are strengthened the KPI relative ELO can be improved significantly.

6.4 Comparison of results with other research

Kroposki et al. [48] concludes that 100 % renewable grids require significant curtailment of renewables. The scenario simulations on Austrian federal state level presented here clearly show that curtailment of renewable generation can be avoided by strengthening only a few transmission lines.

A PtG deployment scenario review by Eveloy and Gebreegziabher [49] shows that research regarding PtG deployment is mainly attached to excessive renewable energy generation. PtG facilities contribute positively to avoid curtailment of renewable generation, grid stabilization and improvement of energy supply security [49]. Schwarz et al. [50], discuss the positive systematic effects of PtG in energy systems with high degree of renewable penetration.

Our Simulations also show, similar to their results, positive impacts of flexibilities such as PtG on electricity grids.

7 Conclusions

Within this work we discuss general aspects on modelling, designing and operating of MES, coupling the grid

Table 5: Comparison of KPIs for both scenarios

	Scenario 1		Scenario 2	
KPI	**Base case**	**Advanced case**	**Base case**	**Advanced case**
DSS electricity	58 %	81 %	75 %	93 %
DSS natural gas	0 %	1,1 %	0 %	4,4 %
share of RES	97 %		125 %	
DRE	84 %		100 %	
Rel. ELO	0,41 %	1,49 %	1,25 %	3,90 %
Primary energy demand	36.600 GWh	32.100 GWh	35.900 GWh	29.400 GWh

bound energy carrier electricity, gas, and heat. Such systems allow for a better integration of volatile renewables and provide the opportunity for an enhanced primary energy efficiency, compared to current energy systems with decoupled energy carriers.

When modelling such MES, beside the volatile behaviour of future generation and demand, also their spatial distribution has to be considered. Therefore, we introduce a cellular approach which facilitates balancing energy production and demand on the lowest cell level being implemented. In order to investigate grid congestions, resulting mainly from RES expansion, exact load flow calculations of all energy carriers have been applied. A measure for mitigating such congestions is the appropriate design- and operation of flexibility options. MES-flexibility options are particularly interesting, since they enable cross energy carrier seasonal storages.

All these mentioned aspects are integrated in our MES modelling framework HyFlow. The framework is a unique MES simulation tool that allows scenario based analysis of future MES with a technical focus on infrastructure and flexibility options. Results from the investigated scenarios can provide decision support, especially for grid operators and political decision makers.

The capabilities of HyFlow are presented on the example of two scenarios. In both we demonstrate, that an expansion of RES can be realised with few improvements of the current energy infrastructure. The implementation of energy storages and MES elements, as for instance PtG, facilitate grid relief. However, the location of flexibility options has to be selected carefully. If misplaced or oversized, flexibility options can benefit overloads at certain grid sections, as both scenarios display. Overloads can be avoided by either strengthening particular grid sections, or several decentralised facilities instead of a central one.

The HyFlow framework can be further improved in areas such as load flow calculation, grid depiction and operational strategies of both storage and hybrid technologies. We continuously aim to improve HyFlow based on feedback from its application in research projects.

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