DELIVERABLE 2.1: DESCRIPTION OF THE CURRENT SITUATION

FFG Projektnummer	848778	eCall Antragsnummer	5160132
Kurztitel	OptHySys	FörderungsnehmerIn	AIT
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1. Overview

Work package 2 aims at a detailed technical concept for the integrated operation of hybrid thermal-electric energy systems. This technical concept serves as the basis for modeling the electrical and thermal networks and their coupling points in the considered uses cases. Within this context, deliverable D2.1 covers the following points:

- description of the topology of the thermal and electrical networks (without coupling), as well as the structure, design and characteristics of the consumers and generators
- description of operating scenarios of the thermal and electrical network (without coupling)
- identification of critical points in existing electrical distribution networks (without coupling)

2. Introduction

Two main objectives were defined for the OptHySys project:

1. analysis of the suitability of thermal-electric hybrid networks in Austria
2. deduction of concrete implementation potentials / potential demonstration projects

In fact, two Austrian network operators (Salzburg Netz GmbH and IKB – Innsbruck municipal utility companies) recognized the importance of the project within a few months, and offered their support. The resulting co-operation led to the definition of two specific use cases, based on expected future challenges and driven by the needs expressed by the network operators. As a result, the relevance of the project for future applications and implementation projects was significantly increased in line with the second main objective. In addition, the quality and practical relevance of the available data and models could be improved within the scope of this cooperation, which in the sense of the first main targets will allow for significantly more accurate analysis results.

Two use cases have been compiled and selected for the OptHySys project:

- Use case IKB Demonet comprises a setting typical for Austrian sub-urban industrial parks.
- Use case Köstendorf targets typical Austrian rural residential areas, including small businesses

This report summarizes the description of the thermal and electrical networks as well as their associated producers, consumers and storages. Due to reasons of confidentiality, the level of detail in this report is limited.

3. Use case IKB Demonet

The premises on which the IKB Demonet is intended to be installed are part of a sub-urban industrial park area, comprising multiple office buildings, an industrial facility as well as a green house. The different buildings are located close to each other between the streets Roßaugasse, Langer Weg and Trientlgasse in Innsbruck. Figure 1 shows a map of the targeted area that depicts all the buildings that are considered in this use case.

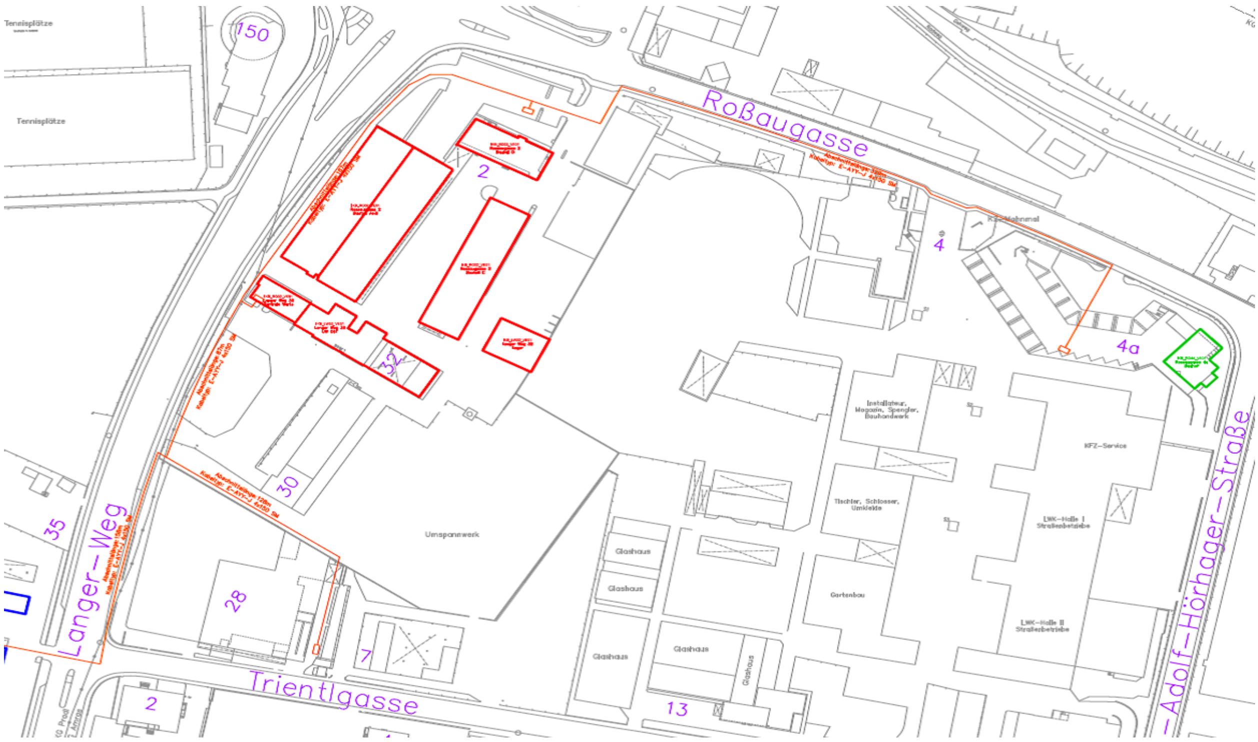

Figure 1: Map of the area depicting the buildings considered in the IKB Demonet use case.

Electrical side

This use case comprises a low voltage network with about 0,6 km cables and 0,615 km overhead lines, which supplies a group of different customers. In addition, there are 5 medium-size PV systems connected to the same network. Figure 2 shows the layout of the existing electrical network and Table 1 gives an overview of the associated electrical consumption and production. The complete information on the thermal grid (incl. consumption and production) has been compiled in a simulation model (compare with deliverable D3.1).

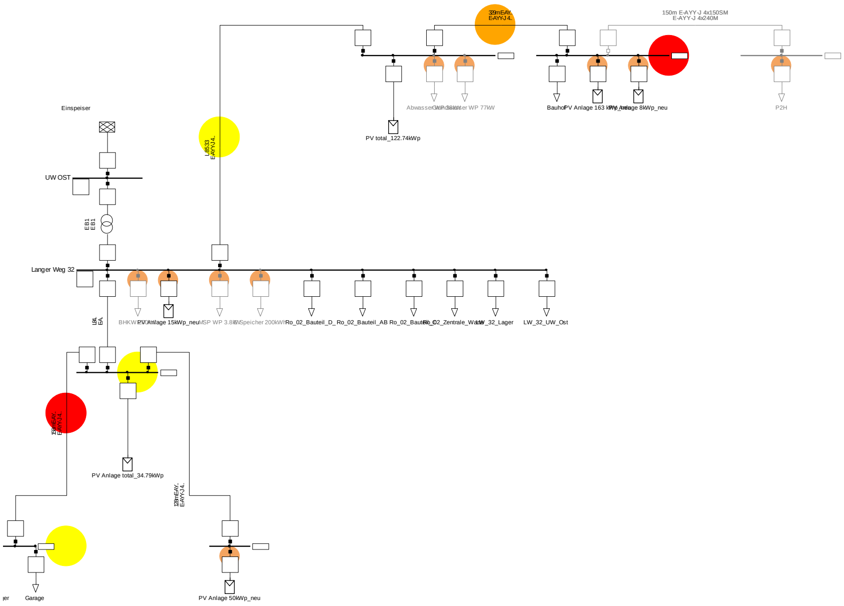

Figure 2: Layout of the electrical network for the IKB Demonet use case.

Thermal side

Today, the heat for domestic hot water (DHW) preparation, space heating (SH) and green house heat is provided by dedicated heat plants directly at the different locations. These heat plants are not interconnected, which does not make it possible to share heat between them. In the following, the heat plants existing today are listed:

- Roßaugasse 2: one gas boiler of 630 kW nominal capacity
- Roßaugasse 4: two gas boilers of each 865 kW nominal capacity
- Roßaugasse 4: one biomass boiler of 950 kW nominal capacity
- Roßaugasse 4a: one gas boiler of 80 kW nominal capacity

Table 2 summarizes the yearly thermal demand (DHW, SH or green house heat) of all buildings based on the data provided by IKB (building's owner and network operator) and SPIEGLTec (consultant for IKB). Figure 3 summarizes the use case from the thermal side. Highlighted customers are considered part of the project as well as current heat plants in place.

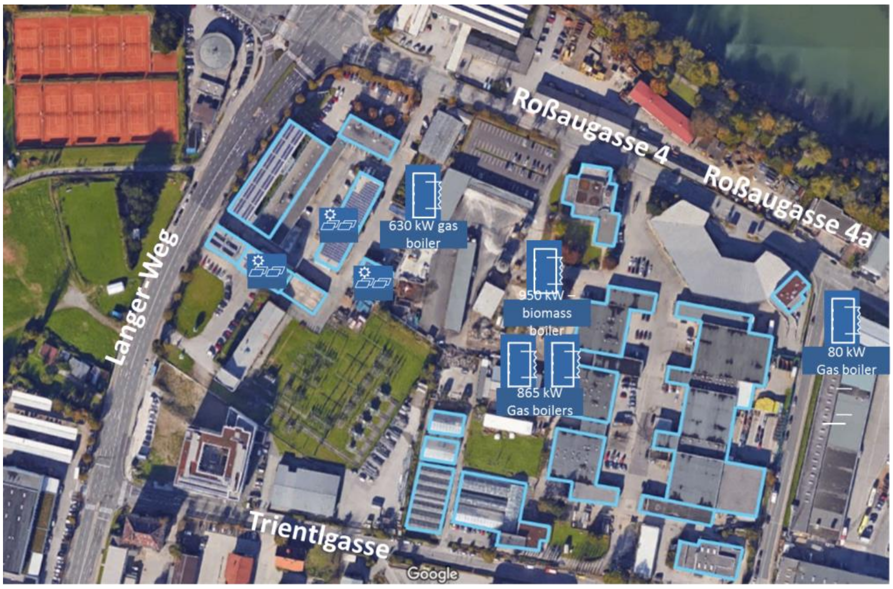

Figure 3: Overview of the thermal grid for the IKB Demonet use case, including customers and plants.

The complete information on the thermal grid (incl. consumption, production and standard operating scenario for the plants) has been compiled in a simulation model (compare with deliverable D4.1).

building	address	electrical demand (MWh)	electrical production (kW)
Bauteil A+ B	Roßaugasse 2	359	123
Bauteil C			
Bauteil D			
LW 32 Lager	Langer Weg 32	236	35
LW 32 Zentrale Warte			
LW 32_UW OST			
Verwaltung Gebäude	Roßaugasse 4	128	--
Zentralhof		293	--
Bauhof	Roßaugasse 4a	54	--

Table 1: Electrical demand and production for different customers in the IKB Demonet

building	address	area (m^2)	thermal demand (MWh)
Bauteil A+ B	Roßaugasse 2	4700	374
Bauteil C		1003	79
Bauteil D		800	63
LW 32 Lager	Langer Weg 32	323	25
LW 32 Zentrale Warte		780	62
LW 32_UW OST		1780	141
Verwaltung Gebäude	Roßaugasse 4	3179	252
Zentralhof		7288	1184
Bauhof	Roßaugasse 4a	750	89
Gartenamt	Trientlgasse 13	2422	407

Table 2: Thermal demand of buildings in the IKB Demonet

4. Use case Köstendorf

Electrical side

Köstendorf comprises a rural low voltage grid (voltage level 400 V) with total cable length of about 6,525 km. This network connects about 96 households, 16 commercial customers, and 2 customers with agriculture activities (about 775 MWh/a). In addition, 36 electric vehicles are supplied with about 34 MWh/a and 43 PV systems are feeding a total of 45 MWh/a (40 kWp).

Figure 4 shows a graphical representation of this distribution network. The topology of the distribution grid, the demand of all customers and the production of all PV units have been analyzed. The resulting information has been compiled in a simulation model (compare with deliverable D3.1).

Figure 4: Graphical representation of the electrical distribution network in Köstendorf.

Thermal side

Currently there exists no district heating network in Köstendorf that supplies the whole area. However, for the purpose of studying the potential benefits of a hybrid thermal-electrical approach for a typical rural settlement, a virtual district heating network has been devised for Köstendorf.

This virtual district heating network has been designed according to the typical needs[1] in rural areas with low heat demand density (linear density of about 520 kWh/y/m and peak load demand of about 2.0 MW). The design of the district heating network considered a connection rate of 100% and typical reference heating systems for the buildings (radiator systems). Table 3 summarizes the customers characteristics (usage, building age as well as heated area) of aggregated customers at the network node positions defined in Figure 5. Heat for domestic hot water (DHW) preparation and space heating (SH) is provided by a dedicated heat plant positioned at a central location, and considering the fact that the focus is not on the heat production technology a generic heat plant is considered (ideal source of heat and sink) for which heat balances can be evaluated. No storage units have been considered for the use case. Figure 5 presents the layout of the aggregated tree network structure. The complete information on the thermal distribution grid has been compiled in a simulation model (compare with deliverable D4.1).

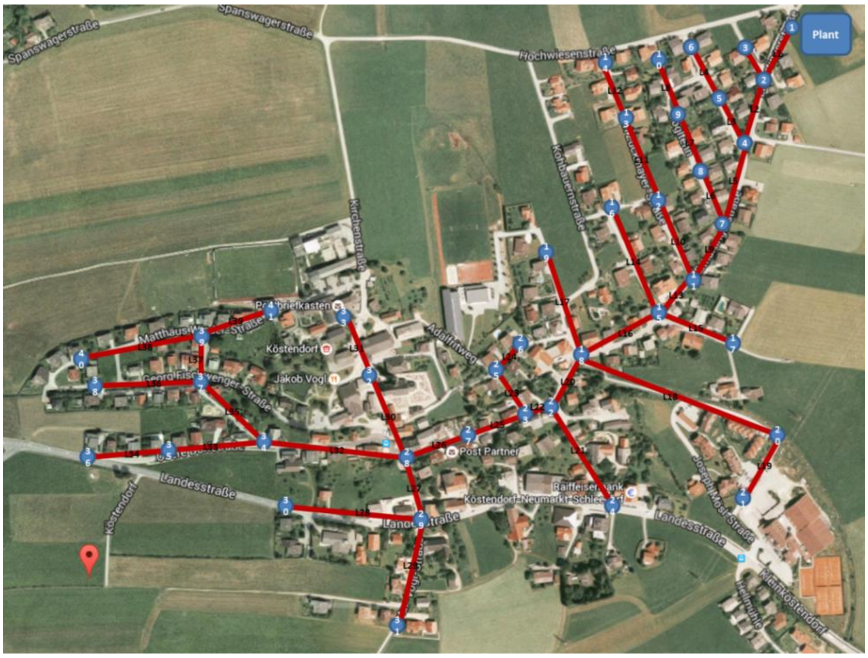

Figure 5: Overview of the Köstendorf Use Case, showing the simplified thermal grid including customers and plant

Critical points

In order to identify adequate locations for additional heat pumps feeding the thermal distribution

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[1] For a summary on typical district heating network structures in Austria, see for instance the analysis of the SolarGrids project: http://www.eeg.tuwien.ac.at/eeg.tuwien.ac.at_pages/research/downloads/PR_382_SolarGrids_publizierbarer_endbericht_v12.pdf

grid, a simulation-based sensitivity analysis has been done. With the help of this analysis, the most critical connection points and lines in the electrical distribution network with respect to the changes in consumption (loads) and generation (PV systems) have been identified.

In the end, three locations have been selected that coincide with nodes that are especially prone to over and/or under voltage problems.

type	number of buildings or flats	building category	building construction age	total heated area [m²]
Plant	-	-	-	-
Customer	7	SFH	1970	805
Customer	60	SFH	1980	6900
Customer	10	SFH	2000	1200
Customer	4	MFH	1970	1980
Customer	2	MFH	1990	1180
Customer	3	Shop	1990	1185
Customer	1	Bank	2000	985
Customer	1	School	1990	1100
Customer	4	SFH	1990	712
Customer	6	Shop	2000	1770
Customer	4	Shop	2000	1180
Customer	4	Shop	1980	1260
Customer	1	School	1990	1100
Customer	1	Gemeindeamt	1980	1400
Customer	29	SFH	2010	4437
Customer	1	Post Office	2000	415

Table 3: Customers characteristics for the aggregated nodes, Köstendorf Use Case

DELIVERABLE 2.2: DESCRIPTION OF PHYSICAL COUPLING POINTS

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1. Overview

Work package 2 aims at a detailed technical concept for the integrated operation of hybrid thermal-electric energy systems. This technical concept serves as the basis for modeling the electrical and thermal networks and their coupling points in the considered uses cases. Within this context, deliverable D2.2 covers the following topics:

- description of physical coupling points between thermal and electrical networks
- definition of potential optimization options for coupling points

2. Introduction

Two use cases have been selected for the OptHySys project:

- Use case IKB Demonet comprises a setting typical for Austrian sub-urban industrial parks.
- Use case Köstendorf targets typical Austrian rural residential areas, including small businesses

This report summarizes the description of the physical coupling points that have been identified as relevant for the use cases. The assessment of the relevance of different types of coupling points is based on internal workshops and discussions with two Austrian network operators (Salzburg Netz GmbH and IKB – Innsbruck municipal utility companies), who supported the project by helping define the use cases.

3. Description of physical coupling points

Heat pumps

Graphical representation

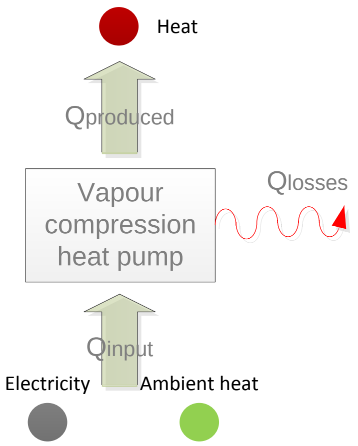

Figure 3: Heat pump model.

Proposed model

Heat pumps might be used for individual applications covering space heating and domestic hot water needs. Heat pumps are usually classified on the basis of the working pair source/sink: water-to-water, brine-to-water, air-to-water. Typically air-to-water heat pumps are employed in small scale applications (single family houses) with coefficient of performance lower than water-to-water or brine-to-water, due to the lower cold reservoir temperatures.

Heat pumps are often used to cover fluctuating heat loads. Various techniques can be used to adjust the heating power to the heat load. The most common techniques are, according to [1] and [2], on/off control and variable-speed control. On-off control consists in alternating on and off phases, thus getting the required modulated heat load. In this case, the maximum efficiency for the system is obtained by minimizing the number of on-off phases, since heat pumps operate in non-optimal conditions during start-up phases (Figure 1). This implies that the design of the heat pump system (including storage) is of crucial importance.

Variable-speed control heat pumps use speed controllable compressors to modulate the heat load. In this case, the system performance reaches an optimum in special part-load conditions, compared to the maximum heat load case. Whereas on-off control heat pumps are normally used in small scale applications, variable-speed control heat pumps are employed in large-scale systems where the modularity of the heat load at high performance level is required.

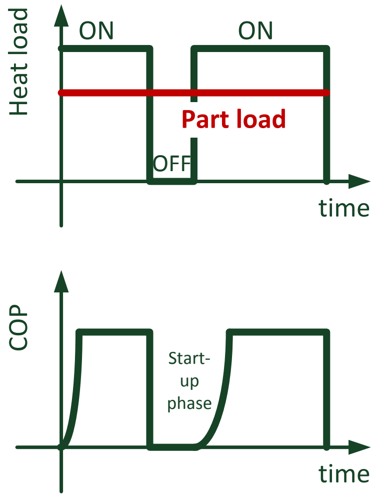

Figure 1: Part load performance for heat pumps: on-off controller strategy

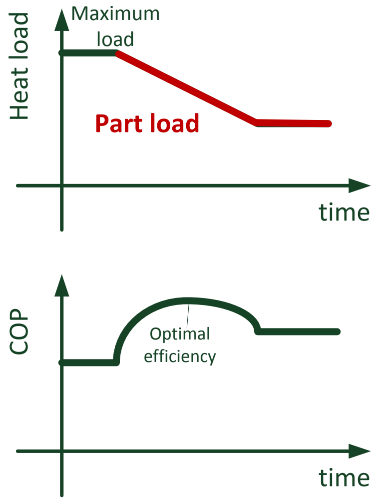

Figure 2: Part load performance for heat pumps: variable-speed controller strategy

The model of a vapor compression heat pump computing the steady-state response is based on the extrapolation of design data. The COP can be characterized as a function of the working pair conditions and nominal heat capacity. Additionally, the efficiency coefficient $\eta_{HP-system}$ takes into consideration the efficiency of the entire heat pump system including storage and auxiliary components, as shown by Equation 2.

$$COP_{HP} = \frac{\dot{Q}_{tot\_heat}}{P_{el}} \qquad \text{Equation 1}$$

$$COP_{system} = COP_{HP} \cdot \eta_{HP-system} \qquad \text{Equation 2}$$

with P_{el} the power consumption of the compressor [kW].

$\eta_{HP-system}$ takes into account the overall efficiency of the system and is around 0.85 (see [3]).

Electrical boilers

Graphical representation

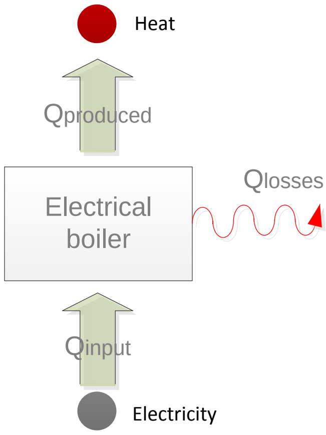

Figure 3: Electrical boiler model.

Proposed model

Electrical boiler can be used to support the operation of heat networks, typically during peak load production. The models of electrical boilers are idealized as lumped system models, applicable both for individual and large-scale applications. The electricity consumption can be assumed therefore as:

$$\dot{Q}_{elec} = \frac{\dot{Q}_{heat}}{\eta_{el\_boiler}} \quad \text{Equation 3}$$

Biomass CHP boiler

Graphical representation

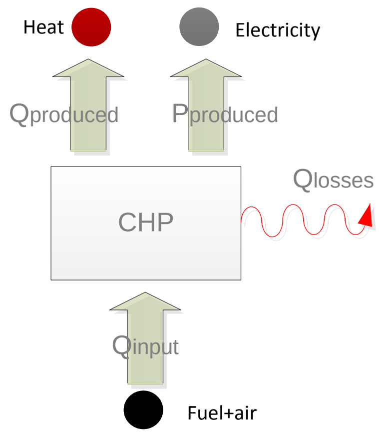

Figure 4: Combined heat and power generation unit

Proposed model

The fuel consumption of a gas turbine CHP (based on the primary fuel specification) can be determined by a black box model calibrated with either monitoring or vendor data. Minimal/maximal off-time and minimal on-time characterises of the CHP model should be considered

The fuel consumption can be assumed as:

$$\dot{Q}_{fuel} = \frac{\dot{Q}_{tot}}{\eta_{tot}} \qquad \text{Equation 4}$$

The efficiency is considered a function of heat to electricity ratio, part load condition of the CHP unit and return temperature of the district heating, Equation 5.

$$\eta_{tot} = \left(\frac{\dot{Q}_{heat}}{P_{el}}, P_{el}, T_{dh,ret}\right) \qquad \text{Equation 5}$$

With:

$\dot{Q}_{fuel}$	primary power of the fuel [MW]
η_{tot}	total efficiency of the CHP [-]
$\dot{Q}_{heat}$	total heat load to the district heating from the condenser [MW]
P_{el}	total electrical power from the turbine [MW]

$\dot{Q}_{pellet}$	total heat load for the steam generation used in the pellet production process [MW]
$\dot{Q}_{tot}$	total power production, sum of heat to the district heating and electricity production from the turbine [MW]
$T_{dh,ret}$	return temperature from the district heating [°C]

From CHP operational data or vendor data the heat to power ratio function in dependency of the part load conditions can be typically expressed as a function of power.

$$\frac{\dot{\mathrm{Q}}_{heat}}{\mathrm{P}_{el}} = f(\mathrm{P}_{el}) \qquad \text{Equation 6}$$

Considering the function from Equation 6, Equation 5 can be simplified as:

$$\eta_{tot} = f\left(P_{el}, T_{dh,ret}\right) \qquad \text{Equation 7}$$

In case the biomass boiler producing steam for the process is not recovering the heat of condensation, Equation 7 can be further simplified (using either operational data or vendor data):

$$\eta_{tot} = g(P_{el}) \qquad \text{Equation 8}$$

In this case the efficiency can be considered as a function of the part load condition, with the relationship between the fuel energy input and the total energy output as in the Equation 9, (coefficient of determination R^2 equal to 0.862).

$$Q_{fuel} \propto Q_{tot} \qquad \text{Equation 9}$$

4. Optimization options for coupling points

The project focuses on the optimization of the operation of hybrid thermal-electrical system from a technical perspective, focusing on the exploitation of synergies between the networks and mutual support in operation. Hence, no monetary optimizations are applied, i.e., neither investment nor operational costs are considered.

Optimization options for Use Case IKB Demonet

Concerning the physical coupling points, the considered degrees of freedom for Use Case IKB Demonet are the following parameters:

- capacity of the waste water heat pump
- capacity of the ground water heat pump
- capacity of the combined heat and power plant (CHP)

Furthermore, variations of the size of the thermal buffers (in Roßaugasse 2 and Roßaugasse 4) are investigated in order to assess their potential impact on heat pump integration.

Optimization options for Use Case Köstendorf

Concerning the physical coupling points, the considered degrees of freedom for the design of the hybrid thermal electrical network in Use Case Köstendorf are the capacities of the three heat pumps.

Furthermore, the sizes of the three thermal buffers (one for each heat pump) are degrees of freedom for the optimization.

References

[1] T. Qureshi und Q. Tassou, „Variable-speed capacity control in refrigeration systems," *Applied Thermal Engineering, vol 16 no 2,* pp. 103-113, 1996.

[2] F. Karlsson und P. Fahlén, „Impact of design and thermal inertia on the energy saving potential of capacity controlled heat pump heating systems," *International Journal of Refrigeration, Volume 31, Issue 6,* pp. 1094-1103, 2008.

[3] M. Miara, D. Günther, T. Kramer, T. Oltersdorf und J. Wapler, „Heat pump efficiency - analysis and evaluation of heat pump efficiency in real-life conditions," Fraunhofer ISE, Freiburg, Germany, 2011.

DELIVERABLE 2.3:
DEVELOPMENT OF REALISTIC SCENARIOS

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1. Overview

Work package 2 aims at a detailed technical concept for the integrated operation of hybrid thermal-electric energy systems. This technical concept serves as the basis for modeling the electrical and thermal networks and their coupling points in the considered uses cases. Within this context, deliverable D2.3 covers the development of realistic scenarios according to typical Austrian conditions:

- definition of system configurations
- definition of operational strategies for renewable energy sources

2. Introduction

Basis of the technical simulation-based evaluation and optimization of the use cases is an operational strategy that determines how the various components in a hybrid thermal-electrical system interact. This includes the definition of which measurement from the system are required and rules for decisions on which producer/consumers to turn on/off under which conditions.

In this report, the concepts behind the operational strategies for the two use cases defined for OptHySys are explained (IKB Demonet, Köstendorf), based on the underlying optimization targets. In addition, the system configurations of the hybrid thermal-electrical networks are summarized (based on the description of the already existing infrastructure in deliverable D2.1).

3. Use Case IKB Demonet

Optimization target

The following optimization targets have been formulated for this use case:

- maximization of the local consumption of on-site PV production for thermal production
- minimization of on-site CO_2 emissions
- minimization of electricity imported from the external grid

Operational strategy

The actual goal of the operational strategy is to always maintain in all thermal buffers an average operational temperature between 80°C and 95°C, in order to guarantee that the thermal demand can be fulfilled at all times at an admissible temperature level. With this goal in view, the operational strategy then choses the producers in accordance to the optimization targets, which can been translated into the following prioritization scheme:

a. In case there is sufficient PV production, heat pumps are given priority over all other heat producers in order to maximize the consumption of local PV production.
b. In case the heat pumps cannot provide sufficient generation, the biomass boilers are used.
c. In case heat pumps and biomass boilers combined cannot provide sufficient generation, the CHP is used.
d. The CHP is not operated in case there is already stress on the local electrical distribution grid (e.g., overloading of cables or voltage band violations due to on-site PV system), since the additional production would put further stress on the system.
e. In case the demand is still not met, the gas boilers are fired.

For the actual optimization process, this operational strategy has been implemented as an optimal controller, based on a linear optimization problem formulation. It selects the heat sources according the scheme described above and at the same time keeps track of all operational constraints (matching of generation and demand, production thresholds, etc.). This guarantees the optimal operation for a given system configuration. The optimal energy management makes sure that the subordinated process controllers of the producers are led according to these requirements. Local process controllers, however, are not subject of this investigation and are modelled according to the conventional techniques and methods of control engineering such as PID and two-point control.

Please note that the heat pumps are only operated in case there is sufficient generation from the on-site PV system, i.e., the operational threshold of either one of the heat pumps or both is smaller than the output (not the surplus) from the on-site PV system. Also, since this would be in contradiction with the design goal to minimize the consumption from the external grid, the heat pumps are never operated in case the on-site PV production is not high enough.

System configurations

Figure 1 shows an overview of the hybrid thermal-electrical system configuration for use cae IKB Demonet. Based on simulation studies evaluating the status quo (according to deliverables D2.1, D3.1 and D4.1) and discussions between AIT and SPIEGLTec regarding realistic sizing options for the various components, the system configurations described below have been selected as potential design candidates.

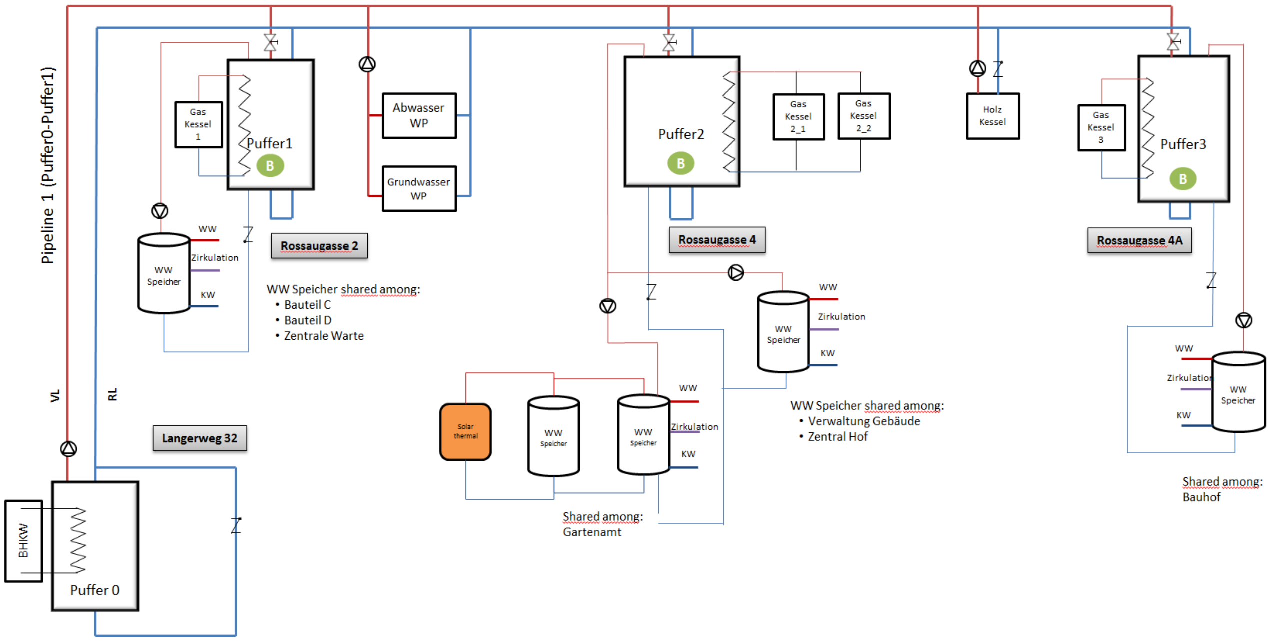

Figure 1: Overview of hybrid system configuration for use case IKB Demonet.

Considered heat pumps layouts

The goal is to maximize the size of the heat pumps such the exploitation of the local PV generation is maximized. However, given the operational strategy explained above, which also aims at a minimization of the electricity consumption from the external grid, the maximal practical size of the heat pumps is limited by the actual PV production. Since the waste water heat pump (AWWP) is always more efficient than the ground water heat pump (GWWP), the AWWP is always used first, whereas the GWWP is only turned on if even more electricity from PV is available and heat is needed. Therefore, all selected configurations foresee a bigger AWWP in combination with a smaller GWWP:

- small size configuration: 100 kW th AWWP & 50 kW th GWWP
- medium size configuration: 150 kW th AWWP & 50 kW th GWWP
- large size configuration: 200 kW th AWWP & 50 kW th GWWP

Considered thermal buffer layouts

The assessment of different thermal buffer layouts aims at maximizing the potential for heat pump integration:

- small size configuration: Roßaugasse 2: 15 m^3, Roßaugasse 4: 25 m^3
- large size configuration: Roßaugasse 2: 20 m^3, Roßaugasse 4: 30 m^3

CHP layout

The current simulation models foresee a 257 kW th CHP (as proposed by SPIEGLTec) which is intended to serve as backup plant for the grid control center. Its additional use for heat production is evaluated as part of the design process.

4. Use Case Köstendorf

Optimization targets

The optimization targets for this use case are:

- Maximization of the local utilization of local PV overproduction for aiding the operation of the electrical distribution network
- reduction of the energy consumption of the central district heating plant
- minimization of electricity imported from the external grid

Operational strategy

Electricity production from PV systems of local prosumers can cause problems in the electrical distribution grid. Especially when PV production is high and electrical consumption is low, the upper voltage limit in the network can be exceeded and lines can be overloaded. Also an undesired reversal of electric energy flow in the local transformer may occur. Therefore, the operational strategy for the use case Köstendorf foresees to utilize this excess energy from PV overproduction in a grid-friendly way. The individual PV systems are used as a *virtual power plant* (VPP) and the controller tries to use as much of the produced net energy locally by operating dedicated heat pumps. Real-time information (with a resolution of 15 minutes) about PV production and electricity consumption is aggregated in order to utilize the otherwise independent PV systems as a VPP.

In the (virtual) district heating system, this additional thermal energy is stored in distributed buffers. These buffers are then discharged in order to help reduce the energy consumption of the central plant. Depending on the outdoor temperature, the minimum operational temperature of the district heating system is between 70°C and 90°C. The controller has to ensure that discharging the buffers does not cause this temperature to drop too low.

The operational strategy can be translated into the following rule-based scheme:

a) In case a violation of the upper voltage limit is detected in the electrical network, turn on the heat pumps and discharge the buffers at an adjusted rate.
b) Do not operate the heat pumps in case the VPP production is not sufficient to power any of them and there are no problems in the electrical network. Instead discharge the thermal boilers as long as their temperatures are above the district heating grid's operating temperature (between 70°C and 90°C, depending on the outdoor temperature).
c) Turn on the heat pumps in case there is sufficient VPP production to power them and there are no problems in the electrical network. Charge the corresponding thermal boilers as long as their temperatures are below 95°C.

In addition to this rule-based scheme, the operational strategy has to determine how to distribute the energy from the VPP production among the heat pumps.

System configuration

In addition to the dedicated plant, the (virtual) district heating network in Köstendorf is fed from distributed thermal storages. Each of these thermal storages is charged by a heat pump.

With the help of simulation-based sensitivity studies of the status quo of the electrical network (according to deliverables D2.1 and D3.1) three adequate locations for the installation of additional heat pumps (and associated thermal storages) have been identified. By placing the heat pumps close to these critical locations, their effect in case of violations of the upper voltage limits is maximized, whereas their impact on the cables and lines is minimized. The maximal size of the heat pumps at each location is limited by the network's capacity to host additional consumers and lies between 100 kW el and 200 kW el.

DELIVERABLE 2.4: DEVELOPMENT OF OPERATING CONCEPTS AND CONTROL STRATEGIES

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1. Overview

Work package 2 aims at a detailed technical concept for the integrated operation of hybrid thermal-electric energy systems. This technical concept serves as the basis for modeling the electrical and thermal networks and their coupling points in the considered uses cases. Within this context, deliverable D2.4 focuses on the following subjects:

- detailed development of operating concepts and control strategies
- definition of potential optimization options for operating concepts

2. Introduction

Optimal performance can be achieved only with the help of an appropriate operational strategy. In general, there are local control systems at the process level (e.g., for heat pumps, cogeneration systems or gas boilers), which are designed to ensure that objectives are achieved locally (e.g., controlling valve positions, keeping supply temperatures constant). However, the complexity of control schemes increases drastically when individual processes are combined to larger system and a new (common) control/optimization target are be defined (e.g., balance between consumption and production with the integration of renewable energy sources). In such a case, a higher control instance (energy management system) is required that in terms of energy efficiency governs the local processes in compliance with all relevant system constraints (e.g., minimum or maximum system temperatures).

In the OptHySys project, two complementary approaches have been tested in this context:

- The simplest approach for control is based on the formulation of specific rules. Given a set of inputs corresponding to a certain system state (measurement data), decisions are taken based on the evaluation of predefined instructions. Such an approach is rather easy to implement in procedural programming languages, but it may require fine-tuning of settings, e.g., parameters corresponding to on/off thresholds.

- In case the system behavior is known or can be adequately described using mathematical models, model-based control schemes can be used to govern the overall system along an optimal trajectory. At runtime, feedback from the system (measurement data) is used to provide safe operation (i.e., in compliance with the necessary system restrictions) at optimal cost.

In both cases the control strategy (or rather an actual implementation of such a strategy) can be evaluated with the help of the co-simulation environment developed in work package 5. However, the conceptual approaches for these two cases for aiding/optimizing the design of a hybrid energy system are different:

- Evaluating a specific system configuration with the help of a rule-based control strategy provides by itself little or no information about how this specific system configuration could be optimized, since improvements could be potentially achieved by changing either the design (e.g., sizing of components) or the settings of the control strategy (e.g., on/off thresholds). Optimization is only feasible through the evaluation and comparison of different design options and/or controller settings. Since in realistic applications the number of possible combinations can be very large, a comparative approach that is both systematic and very fast is necessary (compare with Section 4 of deliverable report D5.1).
- Evaluating a specific system configuration with the help of a model-based optimal control strategy yields a measure for the best possible performance for this specific system configuration. In case only a very restricted number of possible system configurations need to be considered (e.g., due to specific design constraints), the evaluation of all these options yields the best possible design candidate.

The feasibility of both approaches has been tested with the help of the two use cases defined for the OptHySys project (compare with deliverable reports D2.1 and D2.3).

3. Model-based optimal control approach for use case IKB Demonet

This section describes the process of developing a model-based energy management for the IKB Demonet use case. The optimization targets defined in Section 3 of deliverable report D2.3 have been translated to a specific strategy for the energy and cost-optimized operation of the plants, based on detailed component and system models.

Control strategy definition

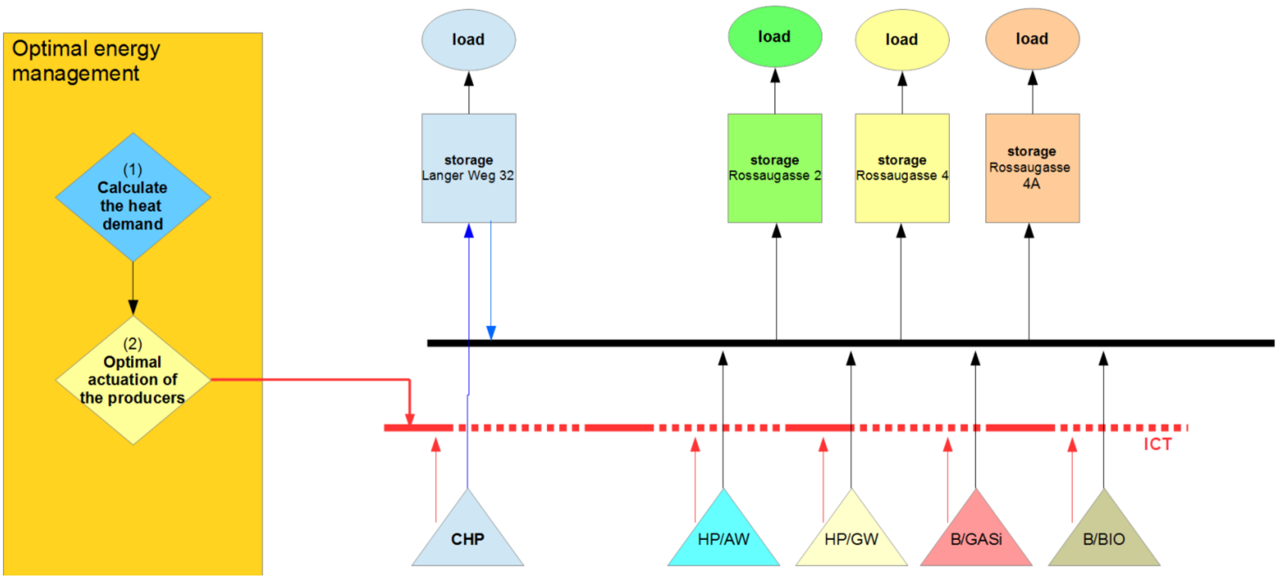

Figure 1: Conceptual view of the energy management system for use case IKB Demonet.

The (local) control strategy for each storage (local process) demands that the flow temperature of the heat supply is maintained at a constant level. The optimal energy management must therefore ensure that for each storage the optimal energy mix of different heat sources (e.g., heat pumps, cogeneration, biomass boilers, gas boilers) is calculated during the operation of the system at runtime. The following criteria have been defined:

a. In case there is sufficient PV production, heat pumps are given priority over all other heat producers in order to maximize the consumption of local PV production.
b. In case the heat pumps cannot provide sufficient generation, the biomass boilers are used.
c. In case heat pumps and biomass boilers combined cannot provide sufficient generation, the CHP is used.
d. The CHP is not operated in case there is already stress on the local electrical distribution grid (e.g., overloading of cables or voltage band violations due to on-site PV system), since

the additional production would put further stress on the system.

e. In case the demand is still not met, the gas boilers are fired.

See also Figure 1 for a conceptual view of the energy management system.

Mathematical formulation

Cost optimality can be formulated mathematically as

$$\mathbf{min} \sum_{i=1}^{n} \int_{t_0}^{T_p} w(i)\dot{q}(i)dt$$

using the weights $w(i)$ and the heat flows of heat sources $q(i)$.

The time integral of the prediction horizon T_p[1] calculates the weighted energy contribution of each heat source to the overall energy mix for the cost-optimal management of the local process control loops. The optimal trajectory for the system operation results from the solution of the (linear) optimization/minimization problem, in compliance with all essential system limitations (e.g., starting behavior, minimum required power, maximum admissible power).
The solution can be stated as follows:

$$[\dot{q}_{opt}^{\{\mathbf{wp}\}} \;\; \dot{q}_{opt}^{\{\mathbf{bhwk}\}} \;\; \dot{q}_{opt}^{\{\mathbf{bio}\}} \;\; \dot{q}_{opt}^{\{\mathbf{gas}\}}]$$

including the limitations:

$$\dot{q}_{opt}^{\{\mathbf{min}\}} \leq \dot{q}_{opt}^{\{\mathbf{i}\}} \leq \dot{q}_{opt}^{\{\mathbf{max}\}}$$
$$\Delta\dot{q}_{opt}^{\{\mathbf{min}\}} \leq \Delta\dot{q}_{opt}^{\{\mathbf{i}\}} \leq \Delta\dot{q}_{opt}^{\{\mathbf{max}\}}$$
$$i \in \{wp, bhkw, bio, gas\}$$

The above vector summarizes the needs of the lower-level process control loops (i.e., the storage temperature control) and the corresponding optimal allocation for the heat sources.

Implementation of the control strategy

The process-oriented control loops are set to set-point temperature control (two-point control with hysteresis between 80°C and 90°C). With the aid of linear programming, set-points for the optimal heat flows are passed on to the lower-level process controllers. The control strategy has been implemented in MATLAB and coupled to the co-simulation environment (via an FMI-compliant

[1] For the sake of a prediction horizon of 15 minutes is assumed (corresponding to the actual sample rate of the system).

interface).

Figure 2 illustrates the heat needs for the storages (Roßaugasse 2, 4 and 4A) and the corresponding heat mix according to the cost function and the system-specific restrictions. As can be seen in the lower figure, the basic load is covered mainly by the CHP and the biomass boiler. Load peaks are primarily managed by utilizing the gas boilers. In Figure 2 the heat pumps (groundwater and wastewater) were ignored by the energy management system as there was no PV production within the considered time horizon. The actual results for the use case IKB Demonet are available in the deliverable report D6.1.

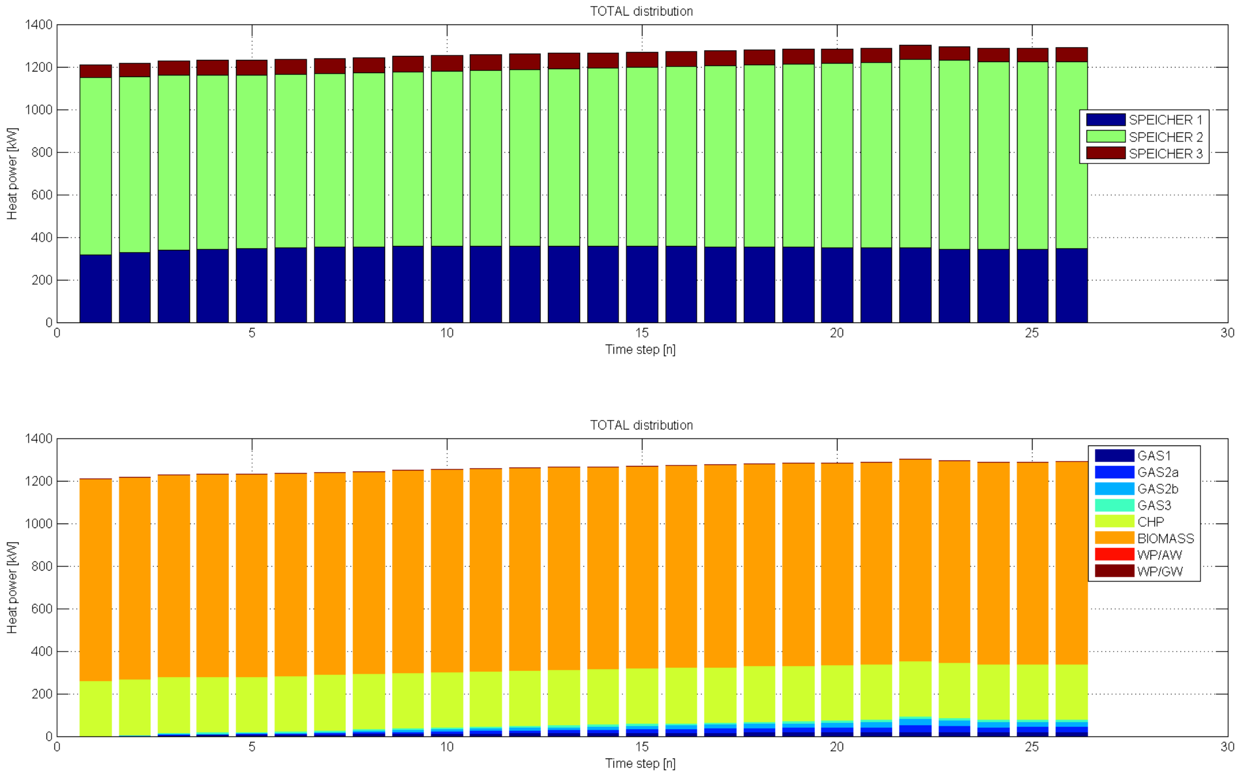

Figure 2: Example output of the model-based control strategy.

4. Rule-based control approach for use case Köstendorf

This section describes the process of developing a rule-based energy management for the Köstendorf use case. The optimization targets defined in Section 4 of deliverable report D2.3 have been translated to a specific strategy for the operation of the heat pumps and the thermal buffers.

Control strategy definition

Electricity production from PV systems of local prosumers can cause problems in the electrical distribution grid. Especially when PV production is high and electrical consumption is low, the upper voltage limit in the network can be exceeded and lines can be overloaded. Also an undesired reversal of electric energy flow in the local transformer may occur. Therefore, the operational strategy for the use case Köstendorf foresees to utilize this excess energy from PV overproduction in a grid-friendly way. The individual PV systems are used as a *virtual power plant* (VPP) and the controller tries to use as much of the produced net energy locally by operating dedicated heat pumps. Real-time information (with a resolution of 15 minutes) about PV production and electricity consumption is aggregated in order to utilize the otherwise independent PV systems as a VPP.

In the (virtual) district heating system, this additional thermal energy is stored in distributed buffers. These buffers are then discharged in order to help reduce the energy consumption of the central plant. Depending on the outdoor temperature, the minimum operational temperature of the district heating system is between 70°C and 90°C. The controller has to ensure that discharging the buffers does not cause this temperature to drop too low.

The operational strategy can be translated into the following rule-based scheme:

a) In case a violation of the upper voltage limit is detected in the electrical network, turn on the heat pumps and discharge the buffers at an adjusted rate.
b) Do not operate the heat pumps in case the VPP production is not sufficient to power any of them and there are no problems in the electrical network. Instead discharge the thermal boilers as long as their temperatures are above the district heating grid's operating temperature (between 70°C and 90°C, depending on the outdoor temperature).
c) Turn on the heat pumps in case there is sufficient VPP production to power them and there are no problems in the electrical network. Charge the corresponding thermal boilers as long as their temperatures are below 95°C.

Implementation of the control strategy

Using a programming language that supports procedural programming (e.g., in C), these rules can be easily translated into executable code and coupled to the co-simulation environment (via an FMI-compliant interface). Figure 3: Example of a rule-based control flow.Figure 3 shows the schematic representation of the rule-based controller used for the proof-of-concept use case in work package 5 (see Section 5 of deliverable report D5.1). The control strategy implemented for the Köstendorf use case follows a very similar scheme.

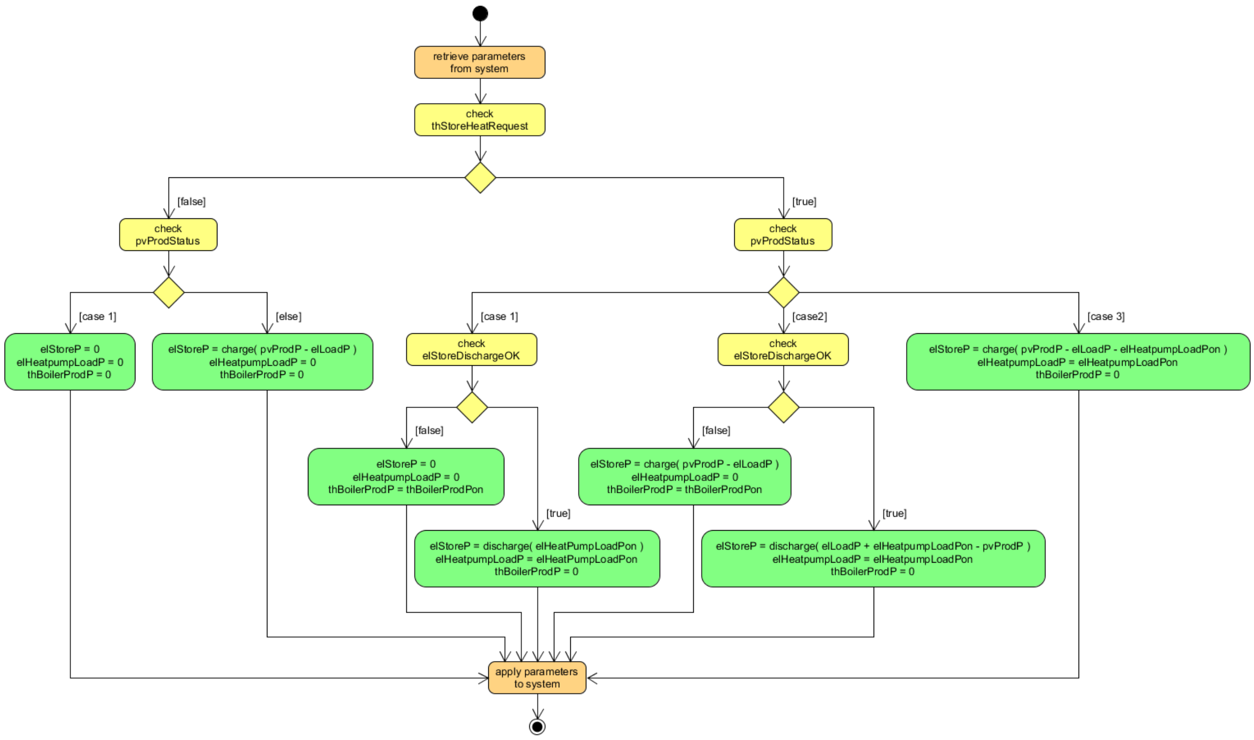

Figure 3: Example of a rule-based control flow.

DELIVERABLE 2.5: DEFINITION OF KEY PERFORMANCE INDICATORS

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Kurztitel	OptHySys	FörderungsnehmerIn	AIT
Bericht erstellt von	Daniele Basciotti, Sawsan Henein, Edmund Widl		

1. Overview

Work package 2 aims at a detailed technical concept for the integrated operation of hybrid thermal-electric energy systems. This technical concept serves as the basis for modeling the electrical and thermal networks and their coupling points in the considered uses cases. Within this context, deliverable D2.5 covers the definition of specific key performance indicators (KPIs) that help evaluate the effectiveness of system configurations and operational strategies.

2. Performance indicators for the electrical domain

The first two technical KPIs apply to the transformer and feeder loading. Together with the voltage quality assessment, the investigation of the transformer and feeder loading results in the hosting capacity of a network and the identification of the limiting factor for this hosting capacity.

Percentage utilization of electricity grid elements

This indicator assesses the loading of grid components and it is widely used among DSOs. It is calculated as both average and nominal value in percentage, i.e., average absolute value of loading of elements and/or number of hours with loading close to nominal loading (following the example for voltage).

$$Utilization_{Average} = \frac{Average\ absolute\ value\ of\ loading\ of\ elements}{Nominal\ loading\ of\ grid\ elements} \times 100$$

$$Utilization_{Nominal} = \frac{Hours\ close\ to\ nominal\ loading\ of\ elements}{Nominal\ loading\ of\ grid\ elements} \times 100$$

Voltage quality performance of electricity

This indicator assesses the voltage quality in a grid and it is described by three different indicators as reported in Table 1. This KPI can be defined as the number of hours where voltage is close to its upper and lower admissible bounds.

voltage disturbance	voltage level	voltage Quality index (limit)
supply voltage variations	LV	• 95% of the 10-minute mean r.m.s values for 1 week (±10% of nominal voltage). • 100% of the 10-minute mean r.m.s values for 1 week (+10% / -15% of nominal voltage)
	MV	• 99% of the 10-minute mean r.m.s values for 1 week below +10% of reference voltage and 99% of the 10-minute mean r.m.s values for 1 week above -10% of reference voltage. • 100% of the 10-minute mean r.m.s values for 1 week (±15% of reference voltage)
unbalance	LV, MV	• 95% of the 10-minute mean r.m.s. values of the negative phase sequence component divided by the values of the positive sequence component for 1 week (0% - 2%).
harmonic voltage	LV, MV	• 95% of the 10-minute mean r.m.s values for 1 week lower than limits provided by means of a table. • 100 % of the THD values for 1 week (≤8%).
mains signaling voltages	LV, MV	• 99% of a day, the 3 second mean value of signal voltages less than limits presented in graphical format.

Table 1: Summary of Standard EN 50160

Level of losses in transmission and in distribution networks

This indicator assesses the level of distribution losses in the whole distribution grid, valid for all voltage level types. This KPI can be defined as followed:

The transport of electrical energy through the distribution or transmission network is associated with a certain amount of losses. Therefore, the amount of energy being produced has to be a few percentage points higher than consumption levels. When the marginal electricity production is based on fossil fuel, as is the case most of the time in most European countries, the losses result in additional carbon-dioxide emissions.

$$Percentage\ of\ Losses = \frac{Amount\ of\ energy\ delivered\ to\ customers}{Amount\ of\ injected\ energy} \times 100$$

Hosting capacity for distributed energy resources in distribution grids

This indicator was chosen for its direct contribution to the project objectives (increasing the amount of renewable energy) and European energy policy. The hosting capacity can be defined as such:

Hosting capacity is the amount of electricity production that can be connected to the distribution network without endangering the voltage quality and reliability for other grid users. To calculate the hosting capacity, it is important that performance requirements for voltage quality and reliability are agreed upon. This could also depend on the type of electricity production; again this means that it is important to define clearly how the hosting capacity is calculated. Incorrect definition or calculation of the index could result in new technology increasing the actual hosting capacity, but not the index.

3. Performance indicators for the thermal domain

The KPIs for the thermal side have been defined in order to assess the sensitivity of the systems from load and generation changes. The most sensitive technical KPIs are used to investigate and assess technical requirements and limitations for the thermal domains of the two use demo sites. Since the optimization targets are different for the Köstendorf and the IKB Demonet use cases, different KPIs have been chosen.

- average heat load demand $\bar{Q}_{heat,demand}$ expressed in [kWh], representing the average total heat demand (space heating and domestic hot water) from all the objects
- maximum heat load demand $Q_{max,demand}$ expressed in [kWh], representing the maximum total heat demand (space heating and domestic hot water) from all the objects
- total heat energy demand Q_{demand} expressed in [GWh], representing the total heat demand (space heating and domestic hot water) from all the objects
- base heat load factor BLF
- maximum heat load production $Q_{max,production}$

- peak oil boiler load factor PLF
- CO_2 emissions expressed in [tons/MWh]
- percentage heat distribution losses q_{losses} [%]

DELIVERABLE 3.1: DOCUMENTATION OF SIMULATION MODELS FOR THE ELECTRICAL DOMAIN

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Kurztitel	OptHySys	FörderungsnehmerIn	AIT
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1. Overview

The main objective of work package 3 is the development of simulation models for electrical distribution networks based on business-as-usual scenarios as well as potential future scenarios. The relevant network topologies according to work package 2 and the corresponding load and generation profiles have been modeled. Based on these models, the coupling scenarios developed in work package 2 from the perspective of electrical distribution networks have been evaluated. The corresponding models have been developed taking into account the prerequisites of work package 5 in order to allow a coupling with the district heating networks from work package 4. This report documents the resulting models.

2. Simulation environment description for the electrical domain

The implementation of the electricity systems (generation units, distribution lines and demand models) were done using the simulation environment DIgSILENT PowerFactory (DIgital SImuLation and Electrical NeTwork calculation program PowerFactory) [1], a commercial tool for power system design and analyses. This computer aided engineering tool is suitable for the analysis of industrial, utility, and commercial electrical power systems. It has been designed as an advanced integrated and interactive software package dedicated to electrical power system and control analysis in order to achieve the main objectives of planning and operation optimization. It is integrating all required functions, fully Windows compatible and combines reliable and flexible system modeling capabilities with state-of-the-art algorithms and a unique database concept.

Network Model

The network model contains all electrical and graphical information and it is divided into the following categories:

- Network Diagrams: Overview, Single Line and Substation Diagrams of all networks
- Network Data: network components, switches, topology, controller models, etc.
- Network Variations: e.g. reinforcements, new lines or stations.
- Additional data like: Areas, Zones, Feeders, Routes, Circuits, Paths, Boundaries, Owners, and Operators.

Interfaces

PowerFactory supports a wide set of interfaces to exchange data with other applications. The interface used in OptHySys project is a FMI-compliant interface [2] that builds on top of PowerFactory's simulation API, which is used for data exchange according to DIgSILENT specific formats.

Level of detail of the modeled grid

An important aspect is the level of details of the modelled power system. Especially, the modelling of low voltage networks with balanced /unbalanced or single phase loads and generators.

The models were designed and parameterized on the basis of three phase balanced connection of both loads and photovoltaics.

Load Flow Analysis

Load flow calculations are used to analyze power systems under steady-state non-faulted (short-circuit free) conditions. Where steady-state is defined as a condition in which all the variables and parameters are assumed to be constant during the period of observation. The load flow calculations were applied in normal system conditions as follows:

- calculation of branch loadings
- transformer loading
- system losses

- voltage profiles.

3. Electricity domain systems models description

Electric system components models in PowerFactory are divided into two main parts: the first one is element general description, and the second one is the element type where specific parameters are defined according to the components manufacture data sheet and/or specifications defined by the distribution network operators. In the second part which is the so called element type, the component is parameterized in different manners and ways corresponding to the technology used the type and target of the simulation done, and also the technical constraints and requirements to be investigated.

Transformer model

The two-winding transformer model is detailed model for various kinds of three-phase, two-winding transformers in power systems. It is used to describe the element general description part of the model. The general model is valid for all PowerFactory calculation functions. Particular aspects such as saturation or capacitive effects (only relevant for some calculation functions like Load Flow and RMS simulations) are described in the type of element part. All parameters are defined according to the specifications of the network operator IKB. The required parameters depend on the purpose, the type of the simulations and also on the operational and technical conditions required to be investigated. In general, the network model presents low voltage level 10 kV/0.4 kV.

Distribution lines models

As aforementioned the distribution lines models are also divided into two parts. The general one which is the element data (*ElmLne*) and the specific part which is line type (*TypLne*), where parameters are defined according to the specifications of the network operator IKB are done for the simulation types.

This part of the document describes the simulation model of distribution lines used in PowerFactory to describe the lines and cables of the IKB demo net. The model uses the equivalent PI-circuit to represent AC transmission lines with lumped parameters over phase technology (3ph, with/without neutral conductor and ground wires).The ElmLne element is used to represent transmission lines/cables. It requires a reference line type.

Models based on line types are by default not frequency-dependent. The electrical parameters are defined per unit-length of the line at power frequency. These parameters remain unchanged; if the frequency of the simulation changes i.e. differs from the power frequency, then the program will adjust the reactance and susceptance of the line according to the new frequency. The inductances and capacitances remain however unchanged.

Load models

Static load models are used for IKB demo net considering voltage dependency. The general load element (*ElmLod*.) in PowerFactory may be used in conjunction with the general load type (*TypLod*). The load element contains all of the operational data associated with the particular load being modelled, and the type contains the non-specific data required for the modelling of that particular class of power system equipment.

Load Flow Analysis

The load is specified as balanced for the state of the art analysis. Additionally, the input parameters for the load is specified based on the load data available from IKB network operator, the appropriate combination of parameters can be selected from the following: S (apparent power), P (real power), Q (reactive power), cos (phi) (power factor) and I (current). The available data is P (real power). For load flow analysis, it suffices to only specify the electrical consumption of the load called general load model. Other data characterizing a load, such as the number of phases and the voltage dependency factors are defined in the general load type (i.e. the Type assigned to the load element). For performing load flow analysis, the technology has to be defined which is (*3-PH-N*) for IKB demo net load models.

Photovoltaic

Photovoltaic generation models are considered as negative load flows with profiles generated based on measured data. The same models described above for modeling loads are used for modeling the photovoltaic units characterizing their generation with negative profiles.

Load profiles

Load profiles refer both to the profiles of photovoltaic electricity generation (supply side) and to the profiles of the electric energy demand (demand side).

Supply side

Photovoltaic generation models are considered as negative load flows with profiles generated based on measured data.

Demand side

Load profiles were used and generated on the basis of annual measured energy consumption and synthetic normalized load profiles on the basis of Austrian standard profiles for households and for non-residential usage.

4. Final grid model for use case IKB Demonet

This use case comprises a low voltage network with about 0,6 km cables and 0,615 km overhead lines, which supplies a group of different customers. In addition, there are 5 medium-size PV systems connected to the same network.

Figure 1 shows the final grid model of IKB demo net, which is used for the assessment of the technical requirements for the different control strategies and the analysis of the state of the art. The network model contains both physical properties of single components (e.g. properties of cables, transformers, etc.) and a graphical visualization of them.

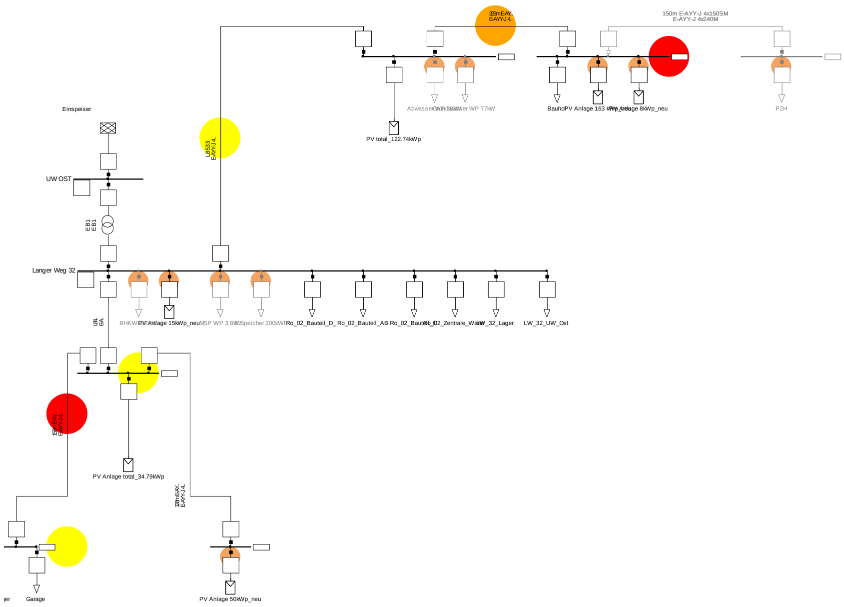

Figure 1: IKB Demonet low voltage network model.

5. Final grid model for use case Köstendorf

Köstendorf comprises a rural low voltage grid (voltage level 400 V) with total cable length of about 6,525 km. This network connects about 96 households, 16 commercial customers, and 2 customers with agriculture activities (about 775 MWh/a). In addition, 36 electric vehicles are supplied with about 34 MWh/a and 43 PV systems are feeding a total of 45 MWh/a (40 kWp).

Figure 2 shows the final grid model of Köstendorf grid, which is used for the assessment of the technical requirements for the different control strategies and the analysis of the state of the art. The network model contains both physical properties of single components (e.g. properties of cables, transformers, etc.) and a graphical visualization of them.

Figure 2:Köstendorf low voltage network model.

References

[1] " DIgSILENT PowerFactory," [Online]. Available: http://www.digsilent.de/.

[2] "The FMI++ PowerFactory FMU Export Utility," [Online]. Available: http://powerfactory-fmu.sourceforge.net.

DELIVERABLE 4.1:
DOCUMENTATION OF SIMULATION MODELS FOR THE THERMAL DOMAIN

FFG Projektnummer	848778	**eCall Antragsnummer**	5160132
Kurztitel	OptHySys	**FörderungsnehmerIn**	AIT
Bericht erstellt von	Daniele Basciotti, Edmund Widl		

1. Overview

The main objective of work package 4 is the creation of simulation models of district heating networks, based on business-as-usual scenarios as well as potential future scenarios. The relevant network topologies according to work package 2 and the corresponding load and generation profiles have been modeled. Based on these models, the coupling scenarios developed in work package 2 from the point of view of district heating networks have been evaluated. The corresponding models have been developed taking into account the prerequisites of work package 5 in order to enable a coupling with the electrical distribution network models from work package 3. This report documents the resulting models.

2. Simulation environment description of thermal domain

The implementation of the thermal domain models is done using the simulation environment *Dymola* [1] based on *Modelica Fluid library* specifications [2] and on the extension of it resulting in the Modelica library *DisHeatLib* [3] developed at AIT. Figure 1 shows an overview of all available components in the DisHeatLib library as well as interfaces to the other domains/tools.

The Modelica language is an open source modeling language, consisting of a language standard definition along with a large collection of basic model components from various fields, the so-called Modelica Standard Library. The Modelica language is built around the two basic concepts of algebraic and acausal modelling. This allows the user to specify his or her models using algebraic equations, either from literature or actually derived from the basic physical properties, and enter them directly into the simulation environment without the need of adaption to the algorithms behind the software. Furthermore, all models are a priori acausal, and allow taking phenomena like changing flow directions into account without having to specify them explicitly in the model. The Modelica language is implemented in several tools, from which Dymola was chosen for the implementation.

Modelling the dynamic behavior of a district heating (DH) network as well as heat demand of buildings and plant systems requires modelling both hydraulic and thermodynamic aspects (pressure distribution, heat losses, building physical properties, etc.). Computational models take into account the network topology, individual pipe properties, pumps, building physics, etc.

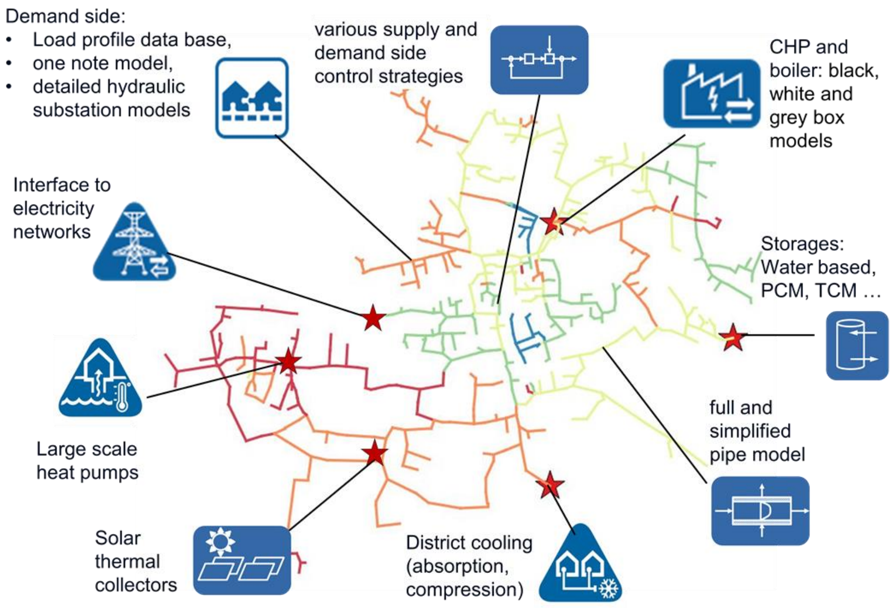

Figure 1: Simulation environment components library.

3. Modeling of weather conditions

Weather data conditions (outdoor temperature and solar radiation) were retrieved from the Meteonorm[1] database and they are referred to the average statistically values from the last 10 years period.

Outdoor temperature

Figure 2 shows an example of an outdoor temperature profile as used for modeling in the OptHySys project.

[1] http://www.meteonorm.com/

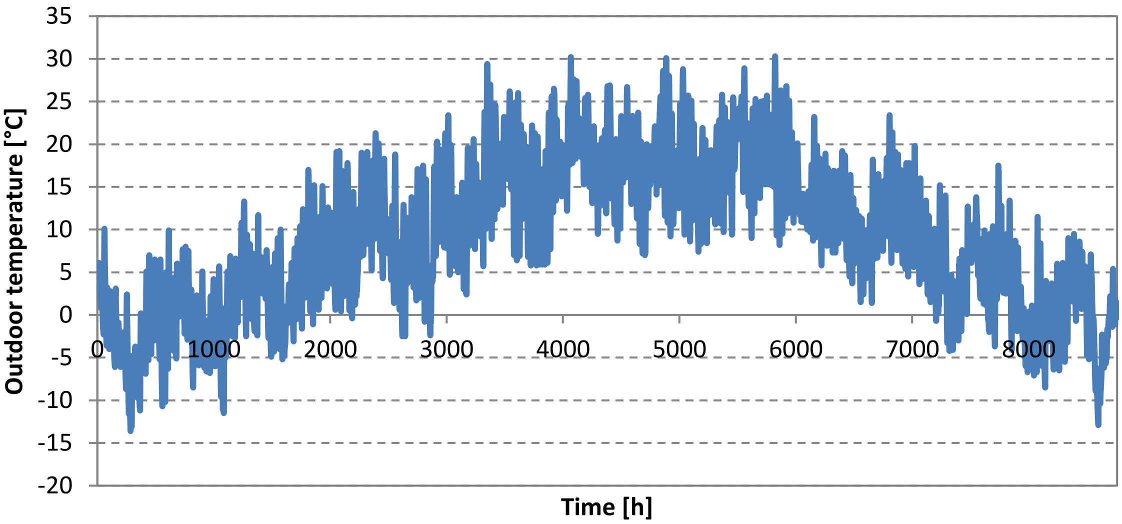

Figure 2: Outdoor temperature

Solar radiation

Figure 3 shows an example of an outdoor temperature profile as used for modeling in the OptHySys project.

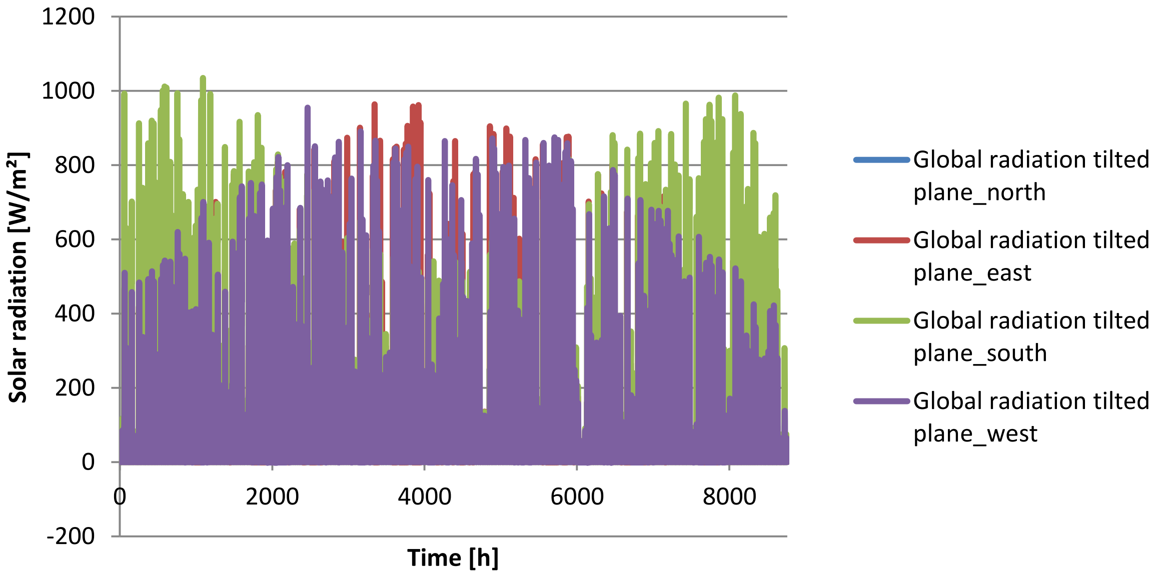

Figure 3: Solar radiation on the tilted plane on the different orientations

Ground temperature

The daily soil temperature at the depth z (in m), is calculated according to the equation below [4]:

$$T_{soil}(z,t) = T_a + A_0 e^{\frac{-z}{d}} sin\left[\frac{2\pi(t-t_0)}{365} - \frac{z}{d} - \frac{\pi}{2}\right]$$ Equation 1

Where the variables T_a and A_0 which represent respectively the average soil temperature (ºC) and the annual amplitude of the surface soil temperature (ºC) are deduced from the monitoring data. t_0 is the time lag (days) from an arbitrary starting date (January 1st) to the occurrence of the minimum temperature in a year. The damping depth of annual fluctuation (in m) is given by $d = \left(\frac{2D_h}{\frac{\pi}{365}}\right)^{1/2}$, with D_h is the thermal diffusivity of the soil (in m^2/s) [5]. The values of the three last variables are assumed based on usual values. The different values used to calculate the daily soil temperatures are presented in table 2. These daily values were then disaggregated into 96 identical daily values in order to fit with the 15 min time step used for the supply and return temperature of the network. The temperature profile of the soil is illustrated by the graph 1.

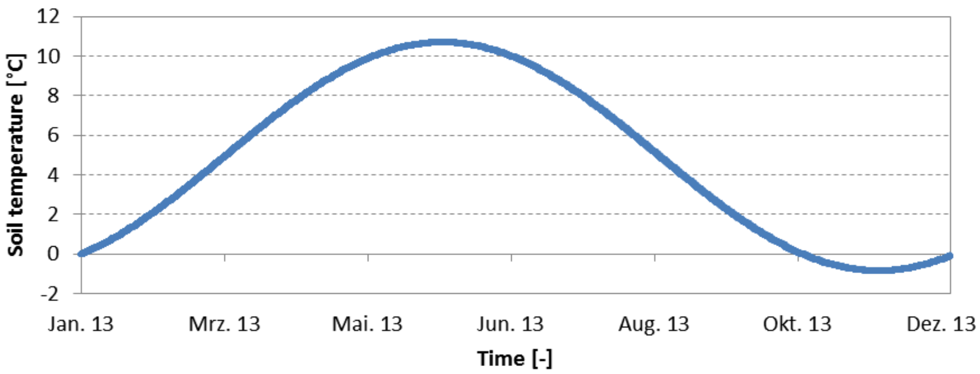

Figure 4: Evolution of the soil temperature over one year (2013)

4. Supply models

BHKW (IET EG 200 V01_50)

The fuel consumption of a BHKW (based on the primary fuel specification) can be determined by a black box model calibrated with technical data (see Figure 5). The fuel consumption can be assumed as:

$$\dot{Q}_{fuel} = \frac{\dot{Q}_{tot}}{\eta_{tot}}$$ Equation 2

The efficiencies as well as the heat and power load are considered functions of part load conditions of the CHP unit as reported in Figure 5.

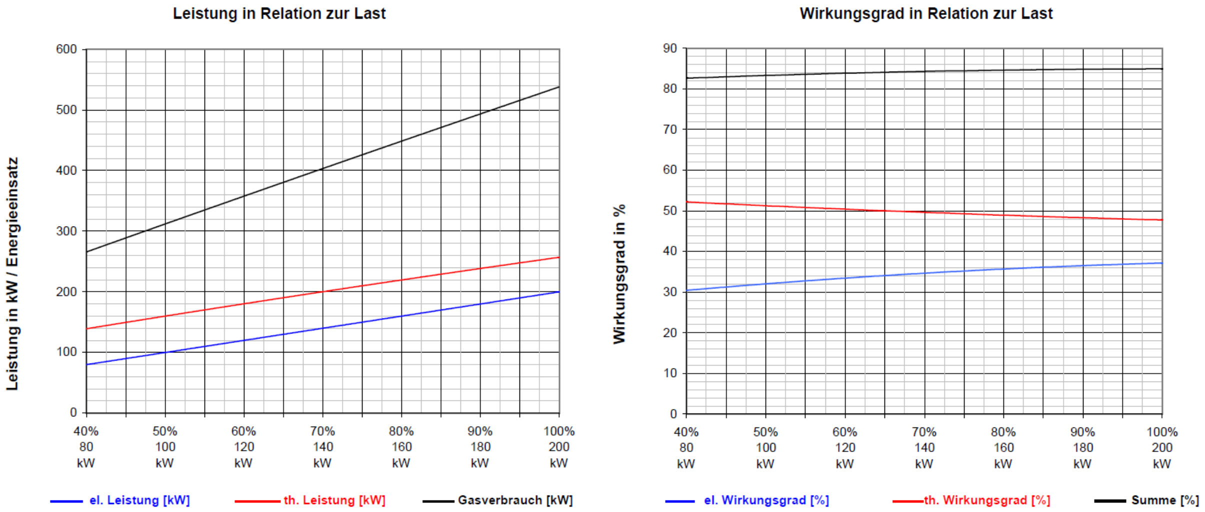

Figure 5: BHKW heat load in relation to the part load condition (left); efficiency in relation to the part load condition (right), technical specifications at design conditions

Biomass boiler (KPT-950)

Biomass boilers are used to support the operation of the DH network in base load coverage. The fuel consumption of the boiler (based on the primary fuel specification) is assumed to be as described in the specifications of the designed plant, see Table 1. The fuel consumption can be assumed therefore as:

$$\dot{Q}_{fuel} = \eta_{biomass\_boiler} \cdot \dot{Q}_{heat} \qquad \text{Equation 3}$$

The efficiency in off design $OD_{eff,\ th}$ of the biomass boiler is described by a function of the part load PF with design value of $D_{eff,\ th}$ = 92% (Table 1). Table 1 summarizes the technical specifications of the plant.

$$OD_{eff,\ th} = D_{eff,\ th} \times (-1.00 \times PT^2 + 1.80 \times PT + 0.17) \qquad \text{Equation 4}$$

			PYRTEC Grate Firing System			
Trade name			**530**	**720**	**950**	**1250**
Item No:			**KPT-530**	**KPT-720**	**KPT-950**	**KPT-1250**
Performance data						
Rated heat output	Q_N	[kW]	530	720	950	1250
Continuous output [1)]	Q_D	[kW]	530	720	950	1250
Minimum heat output [2)]	Q_{min}	[kW]	132	180	238	312
Heat output, W45 chips	Q_{W45}	[kW]	515	700	920	1210
Efficiency in operation to be performed [3)]		[%]	> 90			

Table 1: Nominal capacity and thermal efficiencies of the plant

Heat pumps

Heat pumps have been used to convert (surplus) PV generation (at peak times) into heat and distribute it into the main pipeline. For both models (Ground Water and Waste Water), technical data of a representative Thermea CO_2 heat pump (based on the model HHR180) have been used.

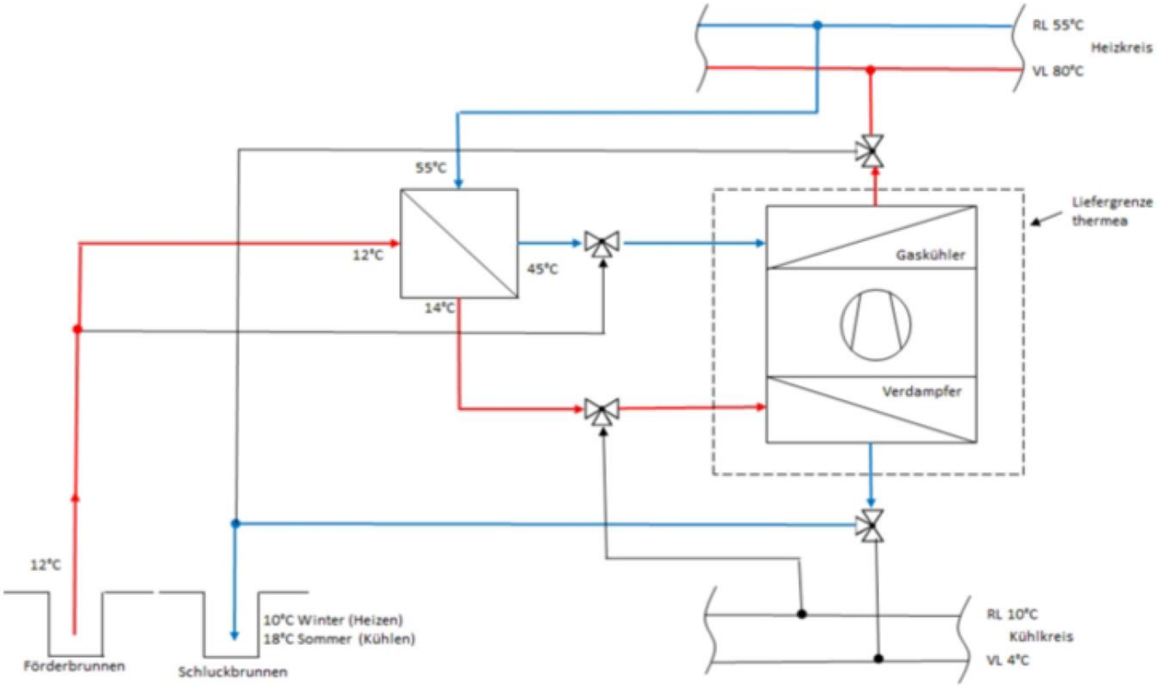

Figure 6: CO_2 Heat pump in winter mode operation (from Thermea)

The model of a vapor compression heat pump computing the steady-state response is based on the extrapolation of design data. The COP has been characterized as a function of the working pair conditions (ground water and/or waste water (source), as well as the district heating supply and return temperatures (sink)) and nominal heat capacity (part load conditions).

$$COP_{HP} = \frac{\dot{Q}_{tot\_heat}}{P_{el}} \quad \text{Equation 5}$$

with P_{el} the power consumption of the compressor [kW].

For both types of heat pumps it is assumed that they have an operational threshold of 60% of their nominal capacity, i.e., they are not operated with a load below this value. For the COP and the heating capacity the following design data have been used in the model:

Load = 100%

sink [°C] return temp 40°C	source [°C] delta T = 3K (except 4°C input --> dt = 1K)							
COP	4	6	8	10	12	14	16	18
60	2.5	2.7	2.9	3	3.1	3.2	3.4	3.5
65	2.4	2.6	2.8	3	3.1	3.2	3.3	3.4
70	2.4	2.5	2.7	2.9	3	3.2	3.2	3.4
75	2.3	2.5	2.6	2.8	3	3.1	3.2	3.3
80	2.3	2.4	2.5	2.8	2.9	3	3.1	3.2
85	2.2	2.3	2.5	2.7	2.9	3	3.1	3.1

sink [°C] return temp 40°C	source [°C]							
Qheating	4	6	8	10	12	14	16	18
60	92	104	116	130	136	142	149	156
65	88	102	112	129	138	143	150	156
70	86	95	109	125	137	143	151	158
75	85	93	104	119	134	145	151	158
80	83	89	99	117	132	144	150	156
85	82	87	97	111	128	141	147	152

Load = 75%

sink [°C] return temp 40°C	source [°C]							
COP	4	6	8	10	12	14	16	18
60	2.5	2.7	2.9	3	3.2	3.3	3.4	3.6
65	2.5	2.7	2.9	3	3.1	3.3	3.4	3.5
70	2.4	2.5	2.8	3	3.1	3.2	3.3	3.5
75	2.3	2.5	2.7	2.9	3.1	3.2	3.3	3.4
80	2.3	2.4	2.6	2.8	3	3.1	3.2	3.3
85	2.3	2.4	2.5	2.7	2.9	3	3.2	3.2

sink [°C] return temp 40°C	source [°C]							
Qheating	4	6	8	10	12	14	16	18
60	71	79	88	98	103	108	113	118
65	68	77	86	97	104	109	114	119
70	65	72	83	95	105	109	115	121
75	64	70	79	92	103	110	115	121
80	63	64	75	89	101	110	115	119
85	62	66	74	86	98	108	112	116

Load = 60%

sink [°C] return temp 40°C	source [°C]							
COP	4	6	8	10	12	14	16	18
60	2.5	2.8	2.9	3	3.2	3.3	3.5	3.6
65	2.5	2.7	2.9	3	3.1	3.3	3.4	3.6
70	2.4	2.6	2.8	3	3.1	3.2	3.4	3.5
75	2.4	2.5	2.7	2.9	3.1	3.2	3.3	3.4
80	2.3	2.4	2.6	2.9	3	3.1	3.3	3.4
85	2.3	2.4	2.5	2.8	3	3.1	3.2	3.3

sink [°C] return temp 40°C	source [°C]							
Qheating	4	6	8	10	12	14	16	18
60	56	64	71	79	83	88	91	96
65	55	62	70	79	83	89	92	96
70	53	58	67	78	85	88	92	97
75	52	57	64	74	83	89	93	97
80	51	54	61	72	82	89	93	96
85	50	53	59	73	80	87	91	94

Table 2: COP and Heating capacity at different load conditions and sink/source temperatures (from Thermea)

Gas boilers

Gas boilers are used to cover the peak needs and the fuel consumption of a gas boiler (based on the primary fuel specification) can be determined by an efficiency curve based on the extrapolations of relevant similar design data. The efficiency in off design $OD_{eff,\ th}$ of the gas boilers is described by a function of the part load PF with design value of $D_{eff,\ th}$ = 95%

$$OD_{eff,\ th} = D_{eff,\ th} \times (4.54 \times PT^5 - 13.96 \times PT^4 + 16.24 \times PT^3 - 8.86 \times PT^2 + 2.21 \times PT + 0.82)$$

Equation 6

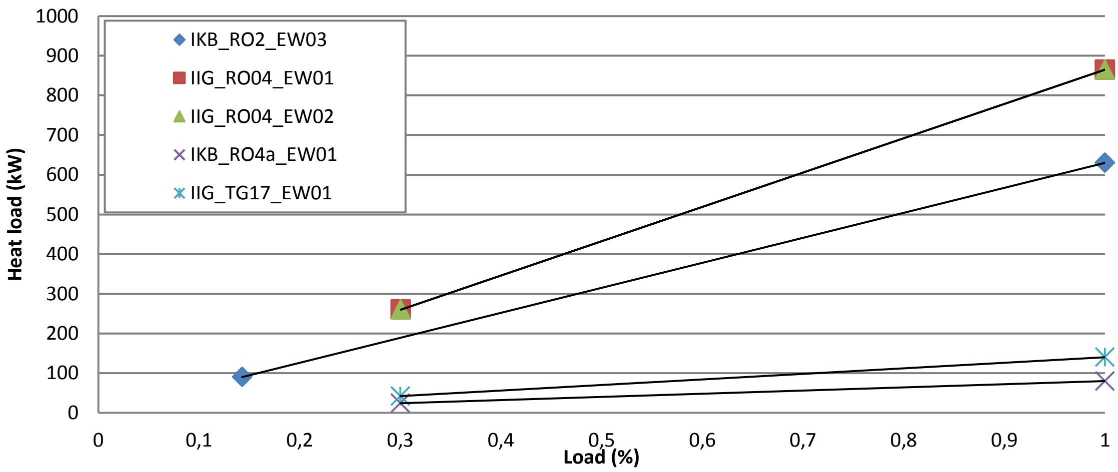

Figure 7: Gas boiler: Heat load in relation to the part load condition for all gas boilers

5. Demand models

Demand models

The heat load demand of customers can be divided into 2 main categories:

$$Q_{tot,heat} = Q_{sh} + Q_{dhw} \quad \text{Equation 7}$$

with

Q_{sh} heating energy demand for space heating

Q_{dhw} heating energy demand for domestic hot water preparation

Domestic hot water preparation

For the residential sector, the tap water profiles were based on the internal AIT DHW profiles generated from statistical assessment of monitoring data from various Austrian district heating networks. Reference conditions for the draw-offs (flow rates, draw-off periods, etc.) and reference conditions for the probability function (daily probabilities for draw-offs etc.), are specified per square meter of heated area

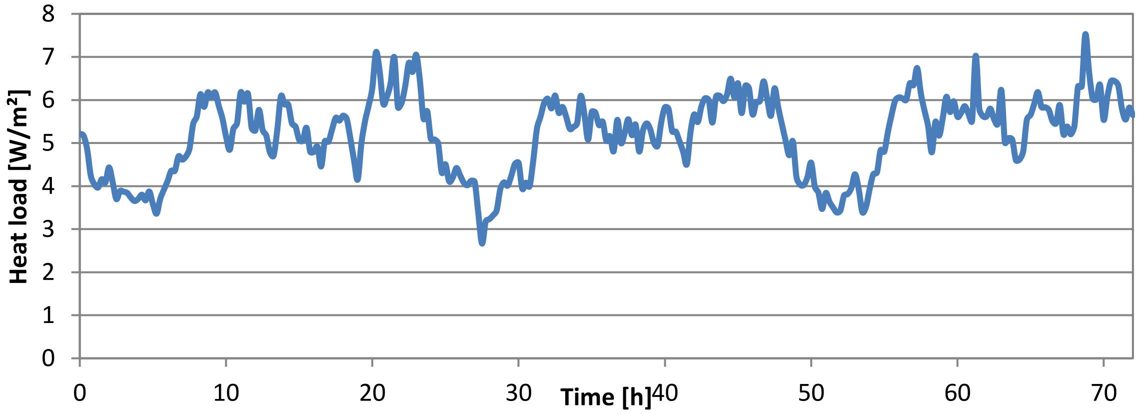

Figure 8: Domestic hot water profile for three days, example

Storage units are implemented in Dymola and tap water profiles are considered for discharging the storage tank (assuming a fixed cold water supply temperature). Auxiliary heating (heat pump, gas boiler or electric boiler) are considered for charging the storage up to a maximum storage temperature at the top layer. Q_{dhw} is the heat load profile as result of the charging phases, and sum of the storage losses and the domestic how water needs:

$$Q_{dhw} = Q_{dhw\_enduser} + Q_{storage\_losses}$$ Equation 8

Following assumptions are considered for both the design and the thermal properties of the storage:

Properties	Value	Assumption
Storage installation	See assumption	Storage capacity 2 times the daily energy consumption accordingly
Specific heat conductivity of insulation	0.04 W/m.K	PUR material
Thickness of insulation	0.1 m	
Ambient temperature	Constant 15°C	Indoor storage installation
Minimum storage temperature	See assumption	SFH no limitations, MFH avoiding legionella
Maximum storage temperature	95°C	Non pressurized tanks

Table 3: Storage tank storage design conditions and thermal properties

Space heating

In contrast to a black box model, a physical building model *RC model* is considered on theoretical basis as described in the VDI 6020 [7]. The dynamic characteristics of a building are represented by interconnections of simple RC circuits. The model is described by two capacities for the thermal storage properties of the building and two equivalent resistances for the heat losses to the environment, which is through walls and ceiling. In addition, the model takes into account the impact of solar gains (with a window model), the heat losses due to leakages (infiltration and ventilation) and optionally the use of HVAC system (radiators/floor heating systems).

An example of parameterization of a low energy standard building model is reported in Table 4, which shows information retrieved from the Tabula/Episcope project for Austrian building standards (containing physical and specific thermal parameters for buildings).

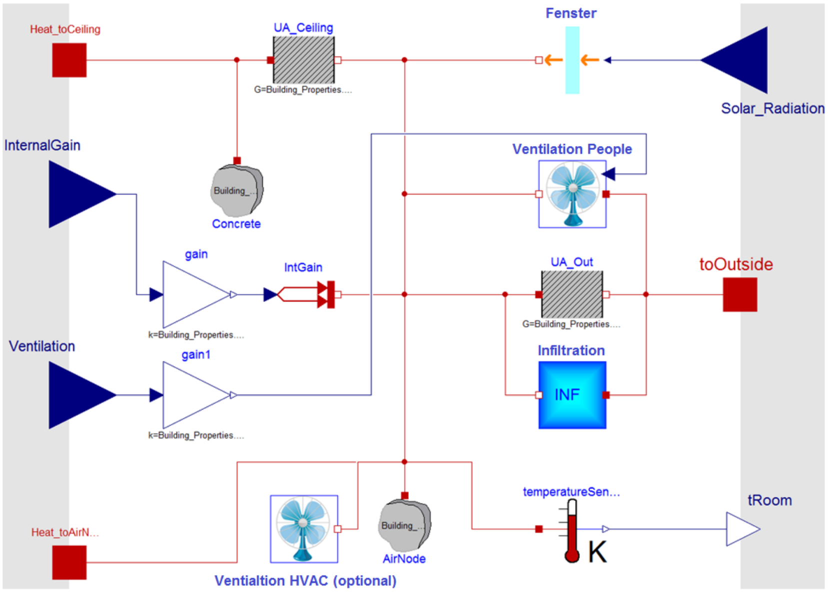

Figure 9: Physical building model.

Input	Type	[-]	*Low energy standard*
	Year of Construction	[-]	2010
	Area	[m2]	150
	Units	[-]	1
	Space heating demand	[kWh/m2.y]	75.00
	Domestic hot water demand	[kWh/m2.y]	32.00
From building standards 2005	FloorHeight	[m]	2.8
	Room height	[m]	2.5
	Number of Floors	[-]	2
	U-Value Roof	[W/m²K]	0.08
	U-Value Exterior Walls	[W/m²K]	0.1
	U-Value Windows	[W/m²K]	1.1
	Wall Window Ratio	[%]	20
	Air tightness	[l/(s.m2)]	0.61 at 50 Pa

Table 4: Example of building physics parameters

Thermal buffer storage

In the IKB use case different sizes of buffer storages have been investigated in different location of the grid. The indirect connection solution (with an heat exchanger) to the customers has been considered as proposed by SpieglTech (see figure). The storage tank is used as energy storage for short time energy buffering. The implementation in Dymola is based on the *StorageStratified* model from the buildings library [8]. The tank uses several volumes to model the stratification and heat conduction between different volumes through the fluid, and between the volumes and the ambient. The tank is discretized into nSeg of fluid volumes. A model discretization example (for nSeg=6) is shown in the Figure 10.

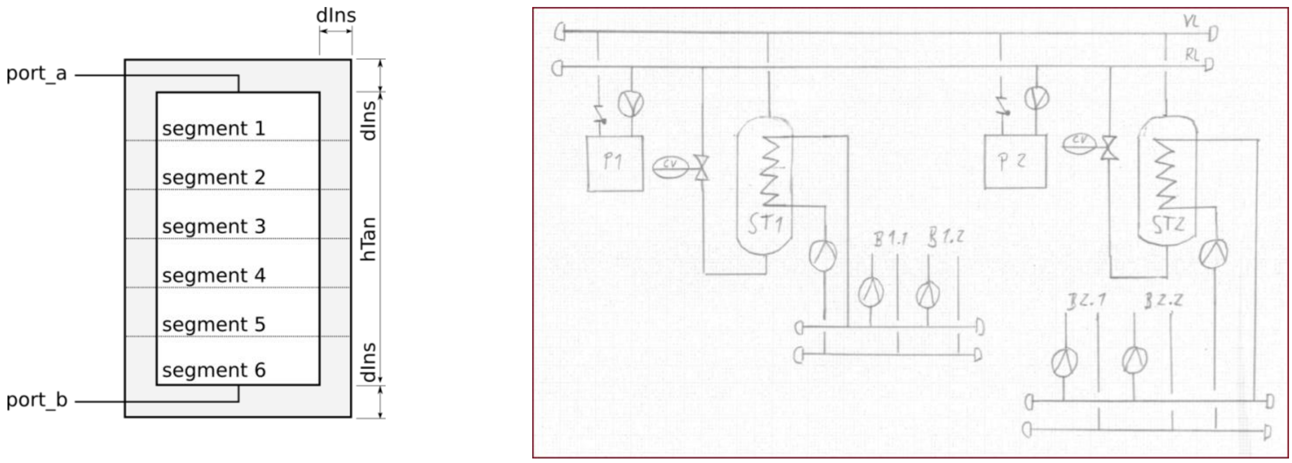

Figure 10: An example of Dymola storage model with 6 layers (left), screen shot monitoring software (right).

Parameters for the Dymola model were taken from the design data provided by SpieglTech and assuming as basis component a 5m³ of buffer tank. In the case of larger buffer tank (e.g. 20m³) a serial connection of 4 buffer tanks is assuming, considering identical parameters as in the following table.

Parameter	Value
Material of the vessel	Steel
Shape type	Cylinder
Material of the insulation	PUR insulation
Insulation jacket	200 mm
Volume	5 m3
Temperature sensors positioning	At each control volume (n=6)
Spray nozzle	Top and bottom piping to avoid stirring and good stratification
Shunt to stop charging	98 °C

Table 5: Parametrization of the storage model in Dymola.

6. Distribution grid model

To describe and analyze the dynamic properties of a district heating grid it is possible to model the entire network taking into account every pipe with the corresponding characteristics (dimensions, material properties, etc.).

The pipe model used in the DH simulation is based on the *Dynamic Pipe*, according to the Modelica Fluid specifications (Figure 11). The model represents a straight pipe with distributed mass, energy and momentum balances and is based on the complete balance equations for one-dimensional fluid flow. The pipe is split into equally spaced segments along the flow path.

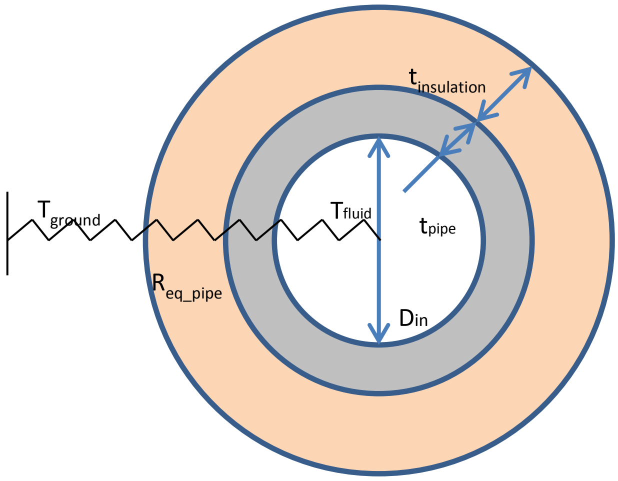

Figure 11: Dynamic pipe mode, according to the Modelica Fluid specifications.

Geometric and energetic parameters in the figure are related to:

$t_{insulation}$	thickness of the insulation material [m]
t_{pipe}	thickness of the pipe material [m]
D_{in}	inner diameter of the pipe [m]
R_{eq_pipe}	equivalent resistance of the pipe between the fluid and the ground temperature (for ground buried pipes) [W/m.K]
T_{fluid}	fluid temperature (e.g. water) [°C]
T_{ground}	ground temperature [°C]

The heat distribution losses for the pipe are modeled as an equivalent thermal resistance between the fluid flow and the ground temperature and the equations are reported below. The main parameters characterizing the pipe that have to be provided to the numerical model are the following:

- DN, nominal diameter
- wall roughness
- overall heat transfer coefficient
- nominal length of the pipe

The heat distribution losses consider the heat dissipated to the environment due to the difference in temperature from the fluid and the ground temperature where pipes are located. It is assumed in the calculation that there is no influence between supply line and return line, therefore the equation for calculating the heat distribution losses can be expressed as:

$$Q_{losses} = U \times L \times \Delta T$$ Equation 9

With U the heat transfer coefficient of pipes (in W/m.K) are reported in Table 6, depend mainly from the pipe insulation, L the total length of the distribution network (in m) and ΔT the temperature difference between the average temperature between supply and return line of the network and the soil temperature T_{soil} (in ºC).

	DN class	D_{in}	D_{ext}	t_{pipe}	lambda	R_{eq_pipe}
Unit	[-]	[m]	[mm]		[W/m.K]	[W/m.K]
Description	*nominal diameter*	*inner diameter*	*outer diameter*	*thickness of steel pipe*	*thermal conductivity of insulation material*	*equivalent thermal resistance*
	DN100	107.1	114.3	3.6	0.024	0.240
	DN125	132.5	139.7	3.6	0.024	0.255
	DN150	160.3	168.3	4	0.024	0.271
	DN200	210.1	219.1	4.5	0.024	0.278
	DN250	263	273	5	0.024	0.274

Table 6: Geometric and thermal parameters of pipes according to DN class.

Typ	Volumenstrom V´ in m³/h		Fließgeschwindigkeit w in m/s		übertragbare Leistung P in kW bei Spreizung					
					20 K		30 K		40 K	
	von	bis	von	bis	von	bis	von	bis	von	bis
KRE - 25	1,148	2,526	0,50	1,10	27	59	40	88	53	118
KRE - 32	2,348	4,695	0,60	1,20	55	109	82	164	109	218
KRE - 40	3,151	6,303	0,60	1,20	73	147	110	220	147	293
KRE - 50	5,879	11,757	0,70	1,40	137	273	205	410	273	547
KRE - 65	9,781	19,563	0,70	1,40	228	455	341	683	455	910
KRE - 80	15,395	30,791	0,80	1,60	358	716	537	1.074	716	1.432
KRE - 100	25,945	51,891	0,80	1,60	604	1.207	905	1.811	1.207	2.414
KRE - 125	49,639	89,350	1,00	1,80	1.155	2.078	1.732	3.118	2.309	4.157
KRE - 150	87,185	152,573	1,20	2,10	2.028	3.549	3.042	5.324	4.056	7.098
KRE - 200	174,732	299,541	1,40	2,40	4.064	6.968	6.097	10.451	8.129	13.935

Table 7: Speed velocities and heat loads of the pipes according to DN class and temperature drops (supply return temperature), ISOPLUS

7. Design of the distribution grid for use case IKB Demonet

Design of the distribution grid is based on the winter coldest day with the assumption of using the building heat demand design conditions and the following priorities: 0) biomass, 1) BHKW. Based on: a) heat flows in the pipeline, b) a conservative assumption of temperature drop between supply and return of 20°C and c) the specifications from the ISOPLUS the pipeline specifications have been retrieved → L1: KRE65, DN65, L2: KRE80, DN80, L3: KRE32, DN32

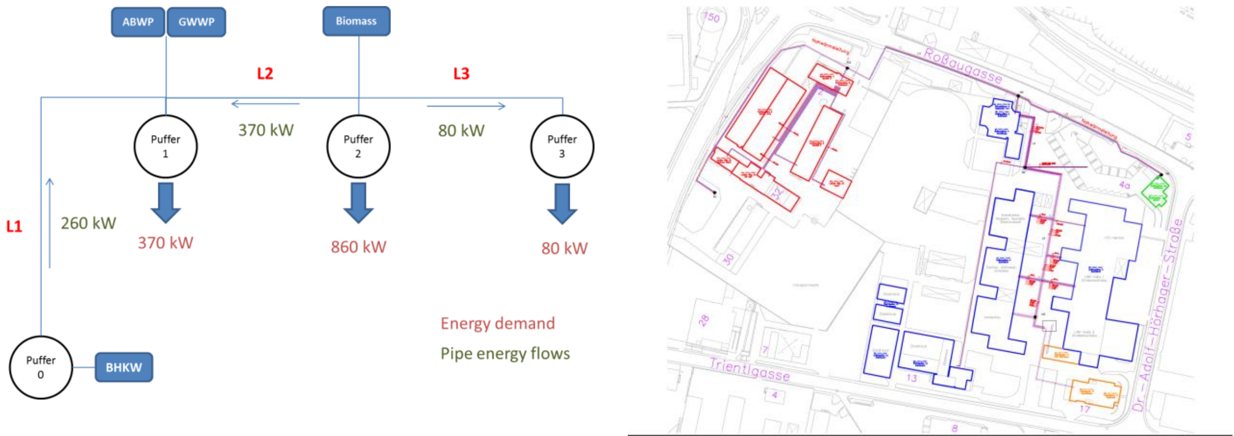

Figure 12: Design heat flows used for the simplified pipeline design.

Space heating profiles are considered based on the results from the one node model as described above. Based on the information of the buildings (data from SpieglTech, containing year of construction and/or renovation per building) and accordingly to the Austrian building standards [6], building physics parameters of each building can be retrieved and used to parameterize the one node model.

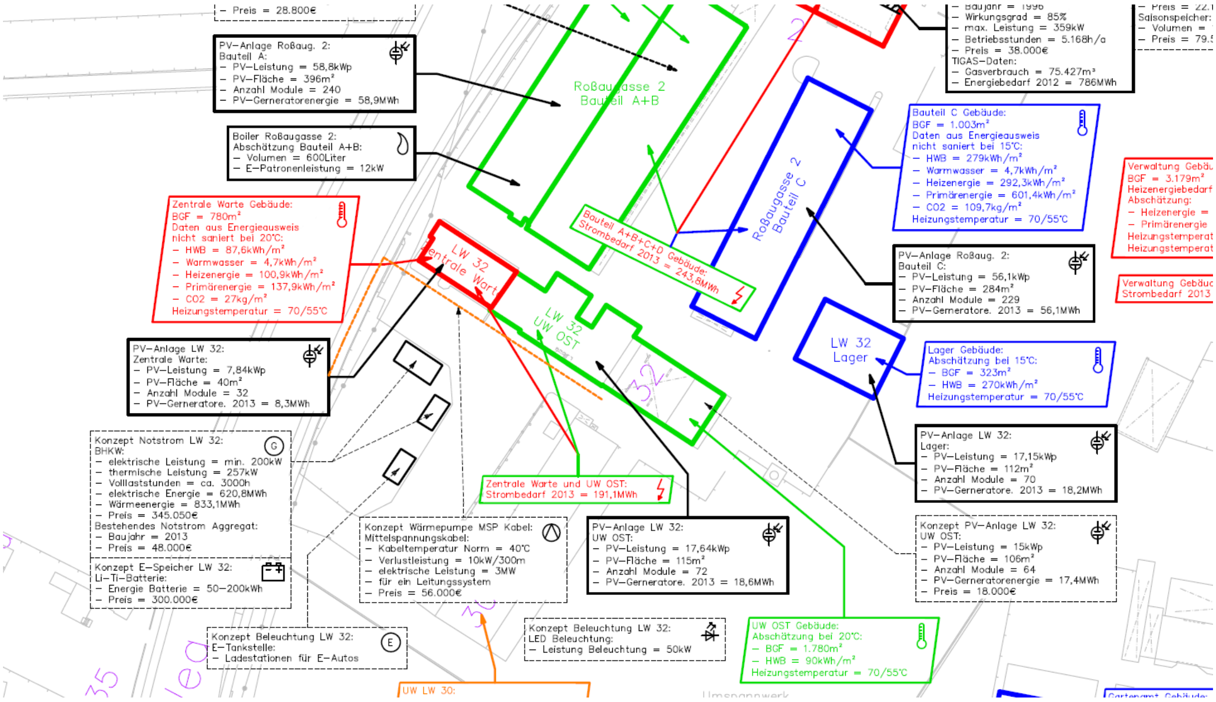

Figure 13: Technical specifications of the building demand (zoom of one part of the IKB use case).

8. Design of the distribution grid for use case Köstendorf

Design of the distribution grid is based on the winter coldest day with the assumption of using the building heat demand design conditions (heat load at -12°C). Based on a) heat flows in the pipeline, b) a conservative assumption of temperature drop between supply and return of 30°C and c) the specifications from the ISOPLUS, the pipeline specifications (nominal diameter) have been retrieved (see Table 8).

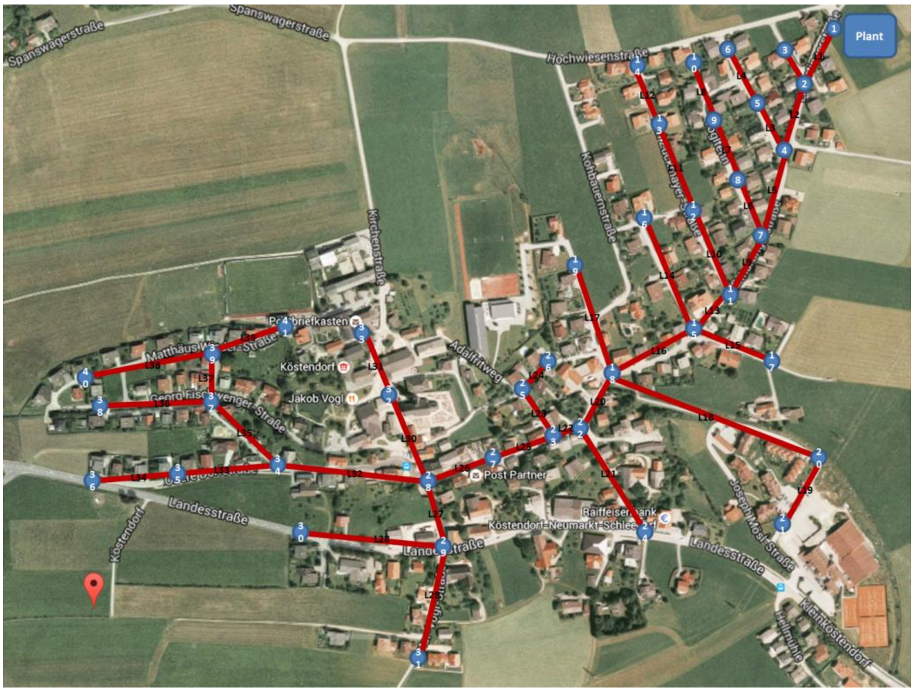

Figure 14: Design heat flows used for the simplified pipeline design.

MAPINFO	DN [-]	length [m]	pktID1	pktID2
1	125	87	1	2
2	125	94	2	4
3	32	60	4	5
4	25	92	5	6
5	125	108	4	7
6	40	69	7	8
7	32	81	8	9
8	25	74	9	10

9	125	78	7	11
10	32	120	11	12
11	32	124	12	13
12	25	65	13	14
13	100	69	11	15
14	32	148	15	16
15	32	96	15	17
16	100	116	15	18
17	32	145	18	19
18	50	272	18	20
19	40	91	20	21
20	100	69	18	22
21	32	139	22	24
22	100	38	22	23
23	40	69	23	25
24	32	53	25	26
25	80	100	23	27
26	80	58	27	28
27	50	86	28	29
28	32	136	29	30
29	32	134	29	31
30	50	151	28	32
31	40	56	32	33
32	65	186	28	34
33	32	106	34	35
34	32	112	35	36
35	50	113	34	37
36	32	172	37	38
37	40	71	37	39
38	32	190	39	40
39	32	72	39	41
40	25	38	2	3

Table 8: DH design of the Köstendorf DH network

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DELIVERABLE 5.1:
DEVELOPMENT OF A SIMULATION AND OPTMIZATION PLATFORM

FFG Projektnummer	848778	eCall Antragsnummer	5160132
Kurztitel	OptHySys	FörderungsnehmerIn	AIT
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1. Overview

The goal of OptHySys work package 5 was the implementation of a co-simulation and optimization platform (deliverable D5.1). This report provides details on the successful achievement of this goal.

Using a tool-coupling approach based on the Functional Mock-up Interface (FMI) specification, a modular and flexible framework has been implemented that enables a detailed analysis and optimization process. The implementation of this software prototype is discussed and its applicability is demonstrated with the help of a use case.

2. Introduction

Traditional simulation tools and models are typically focusing on only one respective energy domain. They are thus not capable of properly describing multi-carrier energy systems in detail (including their controls), which is an important prerequisite for a suitable design process and optimized operation. Tool coupling approaches (co-simulation) provide a promising alternative, facilitating the detailed assessment and optimization of the interactions between the various domains for an in-depth evaluation of the actual synergy potentials.

In this report, a prototype implementation of such a tool coupling approach is presented, relying on established methods and tools where available and extending the state-of-the-art where needed.

3. Co-Simulation of Multi-Domain Energy Systems

Within the context of multi-domain energy systems, the deployment of a tool coupling approach enables domain experts (e.g., thermal, electrical and controls) to use the most appropriate tools for their respective domain. This enables an adequate and precise representation of not only the individual domains but also the complete system.

Within the context of the OptHySys project, the *FUMOLA*[1] environment has been used [1]. FUMOLA is specifically designed to support the features offered by the *Functional Mock-up Interface* (FMI) specification [2], which defines a standardized API and model description for both co-simulation and model exchange. FMI has been selected as it is a non-proprietary, industrial strength specification, developed by both academia and industry.

FUMOLA is developed on top of the *Ptolemy II* simulation environment [3], utilizing the *FMI++ library*[2] for handling FMI-based co-simulation components. The focus of Ptolemy II on the simulation of concurrent processes as well as its capabilities regarding hierarchical and heterogeneous modeling makes it an ideal foundation for a co-simulation environment. By enhancing it with the high-level FMI-based utilities of the FMI++ library, FUMOLA provides a state-of-the-art co-simulation framework that is applicable to a wide variety of applications.

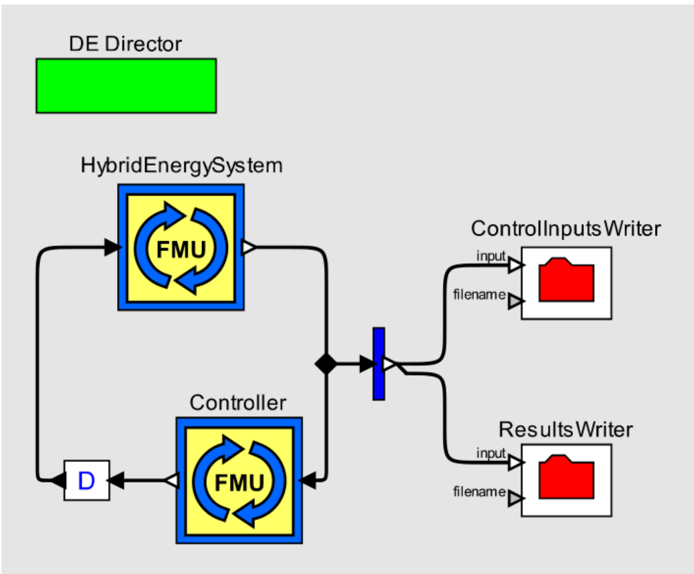

Figure 1: Graphical representation of a co-simulation model.

Figure 1 shows the graphical representation of a co-simulation model as seen by a modeler using Ptolemy II 's graphical user interface. It depicts a typical closed-loop control system model as used

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[1] See http://fumola.sourceforge.net/

[2] See http://fmipp.sourceforge.net/

for the example presented below. For details explaining the functionality of the individual blocks in this model please refer to [4].

4. Optimization of Multi-Domain Co-Simulation Models

Given a system layout with certain degrees of freedom and a design criterion represented by a scalar objective function, the goal is to determine the set of values for these degrees of freedom that minimize the objective function. For energy systems, degrees of freedom could typically be related to the sizing of components (e.g., storage capacities or power ratings) or controller set-points (e.g., gains or thresholds). The objective function maps certain technical and/or economical aspects of the overall system to a numerical scalar value, with smaller values indicating a more desirable performance of the system than higher values. In the case of multi-carrier energy systems, objective functions typically relate aspects of the overall system that are traditionally treated by different engineering domains. Furthermore, objective functions may evaluate effects that result from dynamic interactions between the subsystems, especially synergies between production, consumption and storage and their impact on network operation.

Even though co-simulation approaches are very well suited to evaluate such objective functions for a given system design, their application in the context of design optimization is more challenging. This is mostly due to fact that in general no closed (semi-)analytical representation of the overall system is available, which in turn prevents a closed (semi-)analytical representation of the objective function (or its derivatives). However, even though this prevents the straightforward deployment of many optimization algorithms, it is possible to use metaheuristics that rely solely on the evaluation of the objective function itself.

In the context of this work, the *Differential Evolution* method [5] has been applied. This method optimizes a problem by maintaining a population of candidate solutions and creating new candidate solutions by combining existing ones according to a simple procedure. At each iteration, the candidate solution associated to the smallest value for the objective function is kept. In this way the optimization problem is treated as a black box that merely provides a measure of quality given a candidate solution, without the need of computing derivatives.

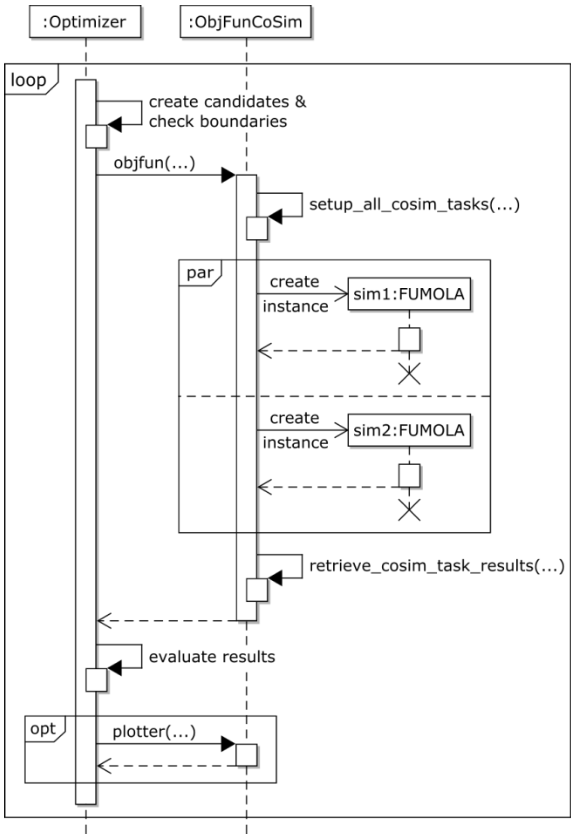

Figure 2: Sequence diagram of the optimization procedure.

Implementation of the Optimization Prototype

The implementation for the prototype presented here is based on openly available MATLAB code[3], containing the algorithm in its full functionality and incorporating bounds, inequality, and equality constraints. In order to adapt this code for the use within a co-simulation environment, the following changes have been made:

- The base class `ObjFunCoSimBase` has been introduced to handle all interactions between the Differential Evolution algorithm and the co-simulation environment. To run an optimization, a class has to be derived that implements the details specific to the co-simulation environment and the system model, referred to as *simulation handler class*.
- Instances of the simulation handler class have to set up co-simulation runs according to the parameters provided by the optimization algorithm (method `setup_all_cosim_tasks`),

[3] See http://www1.icsi.berkeley.edu/~storn/code.html

start the simulations and retrieve the results (method `retrieve_cosim_task_results`).

- The call to a simple objective function has been replaced by a call to the method `objfun` of the simulation handler class.
- Plotting of the results is an optional feature of the simulation handler class, done via a call to the class method `plotter`.
- In the optimizer code, the for-loops used for iterating the candidate solutions have been split up. A first for-loop checks for boundary conditions, then the simulation handler class is called (returning the results for all candidates) and finally a second for-loop evaluates the results.

Figure 2 depicts a sequence diagram of the optimization procedure. The optimization algorithm (`Optimizer`) interacts with the co-simulation environment via an instance of the simulation handler class (`ObjFunCoSim`). When calling the method `objfun(...)`, the simulation handler class translates the optimizer's input, i.e., the parameters of the candidates, into setups for individual co-simulation runs and executes them (ideally in parallel).

The figure only depicts two instances of FUMOLA (`sim1` and `sim2`) that are executed in order to illustrate that the simulations (can) run in parallel, in a real application the number of (parallel) simulation task corresponds to the number of candidates. After all co-simulation runs are finished, the simulation handler collects the results and evaluates the objective function for each. Finally, the optimizer evaluates these results.

5. Example Application: Optimization of a Hybrid Thermal-Electrical Network

An example use case comprising a hybrid thermal-electrical energy system has been used to demonstrate the applicability of the software prototype described above.It demonstrates the applicability of FMI-based co-simulation approaches and their potential benefits for optimizing the design of multi-carrier energy systems.

System Layout

A schematic view of the system layout is shown in Figure 3, with arrows indicating the allowed flows of energy. The modeling of both the thermal and the electrical side relies mostly on power and heat flow balances, ensuring that the demand of the loads is met by the various energy sources. The thermal side comprises a boiler feeding into a buffer, which is connected to the thermal loads. Alternatively, a heat pump can be used to heat the buffer. For the buffer a simple capacitor model is used, linked to a hysteresis controller that signals whether the buffer needs heating in order to keep the temperature in a predefined range. The main source of electricity to meet the demand of the electrical loads is the external grid, but there is also a PV system and a battery available. Similar to the thermal storage, a capacitor model is used for the battery. Realistic profiles are used for the demand of thermal and electrical loads and the production of the PV system. With the profiles used for this work, the system resembles a medium-size commercial site with offices and workshops.

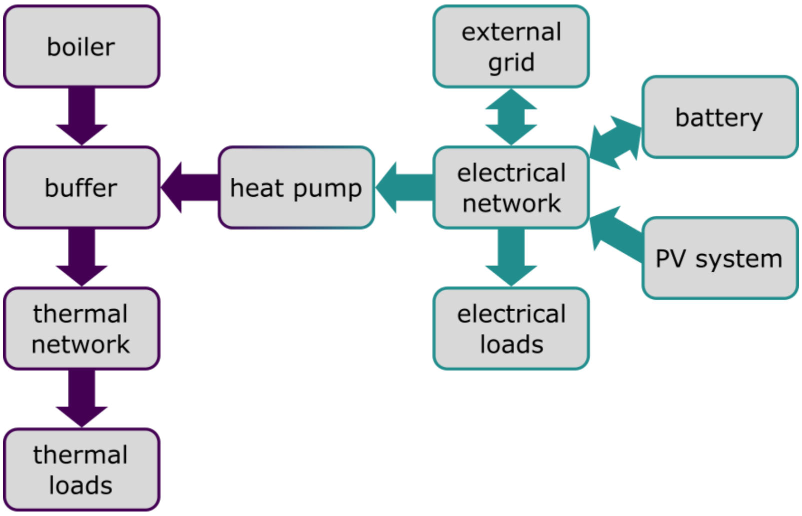

Figure 3: Schematic view of the energy system.

The boiler, the heat pump, and the battery are operated with the help of an *energy management system* (EMS). The EMS aims at two goals:

1. Use local electricity generation from renewable energy sources to operate the heat pump and reduce the utilization of the boiler. Whenever there is an overproduction of PV, i.e., when the PV production is higher than the local electrical consumption, or when the battery is sufficiently charged to power the heat pump, the EMS prioritizes the heat pump over the boiler.
2. Charge the battery whenever there is either PV overproduction and no need to operate the heat pump (no signal from the buffer's hysteresis controller) or enough PV overproduction to have a surplus even if the heat pump is running.

Model Implementation

The FUMOLA co-simulation environment introduced above allows to use the most convenient tools and modeling approaches for different parts of the overall system. For the example at hand, the energy system model can be easily represented with the help of a simple set of algebraic and differential equations (including the buffer's hysteresis controller). MODELICA [6] has been used for modeling and the resulting model has been exported as an FMU for Model Exchange. For the EMS, which follows a rule-based concept, a different implementation approach has been chosen. The EMS was programmed using a procedural language (C/C++) and with the help of the FMI++ library the resulting executable has been wrapped as an FMU for Co-Simulation.

Figure 1 shows the graphical representation of the combined model that has been used for the design optimization.

Objective Function Definition

For the example at hand an object function evaluating only the technical perspective of the system has been chosen, neglecting economical aspects. The design goal is to maximize the exploitation of the local renewable electricity production, in order to reduce boiler operation by using the heat pump. The degrees of freedom in the system layout are the heat pump size, i.e., its electrical power consumption P_{hp} when turned on, and the battery size, i.e., the amount of electrical energy E_{bat} stored in the battery when fully charged.

As a measure for the heat pump's effect on the system, its impact on the energy produced by the boiler E_{boiler} is considered, which should become as small as possible. Its value is calculated from the boiler's thermal power output P_{boiler}:

$$E_{\text{boiler}} = \int_0^T \mathrm{d}t\, P_{\text{boiler}}(t) \rightarrow \min$$

At the same time, the battery's utilization ε_{bat} should be maximized. As a measure for the utilization, the integral of the charging power P_{charge}, normalized with the amount of electrical energy E_{bat} stored in the battery when fully charged, is used:

$$\varepsilon_{\text{bat}} = \frac{1}{E_{\text{bat}}} \int_0^T \mathrm{d}t\, P_{\text{charge}}(t) \rightarrow \max$$

Furthermore, for a given heat pump size P_{hp} the battery size E_{bat} should not be too small, in order to match the discharge power of the battery needed for operating the heat pump (cp. EMS design goal 1) to the battery's capacity. In practice this can be achieved by requiring the numerical value of E_{bat} to be greater than or equal to the numerical value of P_{hp}.

For the purpose of defining an objective function the two equations above are not suitable. Using only the first equation results in unrealistically large heat pump and battery sizes, as this would allow to store all surplus PV production (especially during the summer time) and use it for the operation of the heat pump later on. Using only the second equation results in unrealistically small battery sizes, as this would artificially increase the measure of the battery's utilization.

Ideally, an objective function should penalize too large heat pump sizes, because the necessary battery size would result in a poor battery utilization. At the same time, the objective function should penalize too small battery sizes, as this would result in impractical heat pump sizes. To achieve this goal, both equations can be combined to construct the following objective function:

$$\frac{E_{\mathrm{boiler}}}{(\varepsilon_{\mathrm{bat}})^k} \rightarrow \min$$

The parameter k determines whether the emphasis of the objective function is more towards $E_{boiler} \rightarrow 0$ or $\varepsilon_{bat} \rightarrow \infty$. Due to its definition, the objective function's value increases for both small battery sizes (increase in E_{boiler}) and very large heat pump sizes (decrease in ε_{bat}).

Optimization Results

Figure 4 and Figure 5 show the results for a typical optimization run (using k=1). It used 15 iterations with a candidate population size of 30, with each candidate associated to a full-year simulation run of the corresponding system layout. The computation of the objective function was parallelized by distributing the individual co-simulation runs among 5 client nodes (batch processing). The whole optimization procedure took roughly 25-30 minutes, using 6 computing nodes (1 master node and 6 client nodes).

Figure 4 shows on the left a scatter plot depicting the candidate population evolution in the search space. The color indicates to which iteration a candidate belongs, with darker colors indicating lower iteration numbers. The convergence of the candidate population towards the vicinity can be clearly recognized. The right side of the figure shows the evaluation of the objective function in dependence of the candidates' value for P_{hp}, depicting the convergence of the candidate population towards smaller values of the objective function.

Figure 5 shows the convergence of the optimization parameters. After 15 iterations the best candidate solution found has a heat pump size of P_{hp} = 49 kWel and a battery size of E_{bat} = 49.4 kWh. With this configuration it is possible to substitute 27% of the energy produced by the boiler by operating the heat pump instead, using only locally produced electricity.

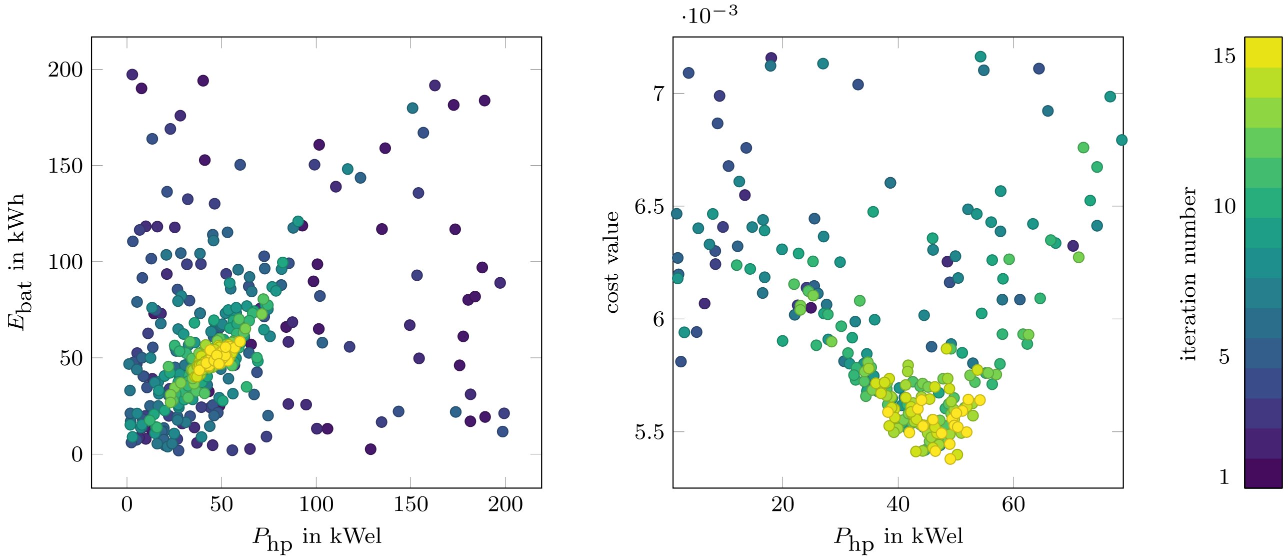

Figure 4: Example of population evolution in the parameter plane (left) and evaluation of cost-function for P_{hp} (right).

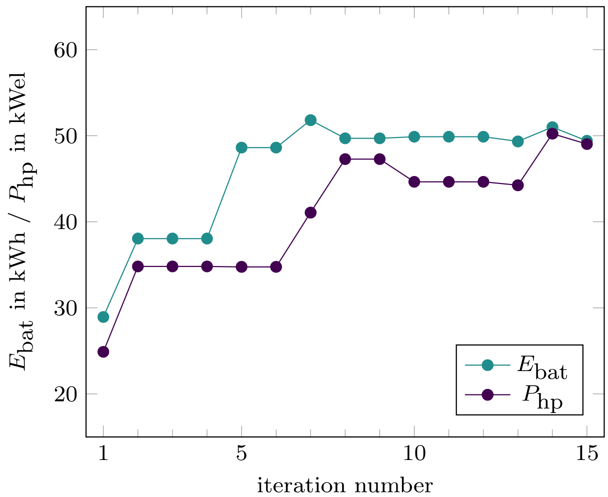

Figure 5: Example of optimization parameter evolution.

Figure 6 depicts optimization results in dependence on the parameter k. Each dot corresponds to the resulting value for P_{hp}, averaged over 15 optimization runs with different random seeds (15 iterations with a candidate population size of 30 each). The gray band indicates the RMS of this average value. As expected, for small values of k the optimization favors large heat pump sizes (and battery sizes), for $k = 0$ the optimization basically yields the largest value allowed within the predefined search interval. Conversely, for large values of k the optimization favors small values of P_{hp}. In the interval k ∈ [0.4, 1.1] the optimization procedure yields basically the same results in all cases, meaning that the objective function is well defined in this interval. For larger values the RMS increases drastically, indicating that the objective function exhibits several pronounced local minima and causing the optimization procedure to give inconsistent results.

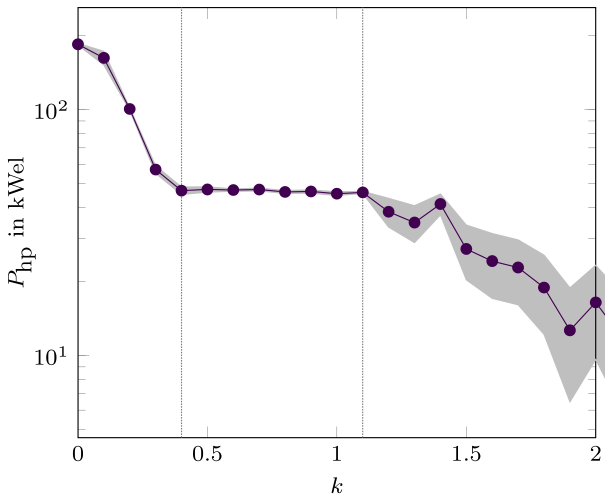

Figure 6: Dependence of optimization result on parameter *k*.

6. Conclusion

Building upon the FUMOLA co-simulation environment and an openly available implementation of the Differential Evolution optimization method, a software prototype has been successfully developed. The feasibility of this approach in general---and the software prototype in particular---for the design optimization of multi-carrier energy systems has been demonstrated with the help of a simple but representative use case. The software prototype is available as part of the FUMOLA environment.

This software prototype is used as the basis for the simulation-based analysis and optimization in work package 6.

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DELIVERABLE 6.1:
SIMULATION, OPTIMIZATION AND EVALUATION OF RESULTS

FFG Projektnummer	848778	eCall Antragsnummer	5160132
Kurztitel	OptHySys	FörderungsnehmerIn	AIT
Bericht erstellt von	Edmund Widl		

1. Overview

The goal of OptHySys work package 6 is to study and quantify the effects of the concepts developed in work package 2. Using the simulation framework developed in work package 5, high-detail, dynamic computer simulations are carried out, which allow a calculation of relevant performance indicators.

2. Introduction

Determining the optimal design is based on the assessment of the results from a model-based evaluation of the hybrid thermal-electrical system, relying upon detailed technical simulations of not only the individual subsystems but also their dynamic interactions. This is done with the help of a co-simulation approach, which couples existing domain-specific state-of-the-art tools in a way that enables a dynamic multi-physics simulation of the hybrid system.

This enables the domain experts (thermal, electrical, controls) to use the most appropriate tools for their respective domain, guaranteeing an adequate and precise representation of not only the individual domains but also the complete system. The considered energy systems, i.e., the electrical network, the thermal network connecting the buildings and as their physical connection points, as well as the controllers have been modelled according to work package 2 (compare with deliverable report D2.1, D2.2, D2.3 and D2.4).

Figure 1 shows a schematic view of a typical co-simulation setup (compare with deliverable report D5.1). The thermal network (modeled in Dymola) and the electrical network (modeled in PowerFactory) are linked through the corresponding physical coupling points. In the co-simulation model they are coupled with each other and connected to the controller in a closed loop. Based on this co-simulation setup, the feasibility of two complementary approaches for optimizing hybrid energy systems have been demonstrated in the context of the OptHySys project:

- In case only a very limited number of possible system configurations need to be considered (e.g., due to specific design constraints), the evaluation of all these options with the help of an *optimal control strategy* yields the best possible design candidate. This approach is demonstrated in the *IKB Demonet use case*.
- In case the number of possible system configurations is large and the evaluation of all possible options is infeasible due to the associated work load, a *meta-heuristic approach* can be utilized to optimize the system design. This approach is demonstrated in the *Köstendorf use case*.

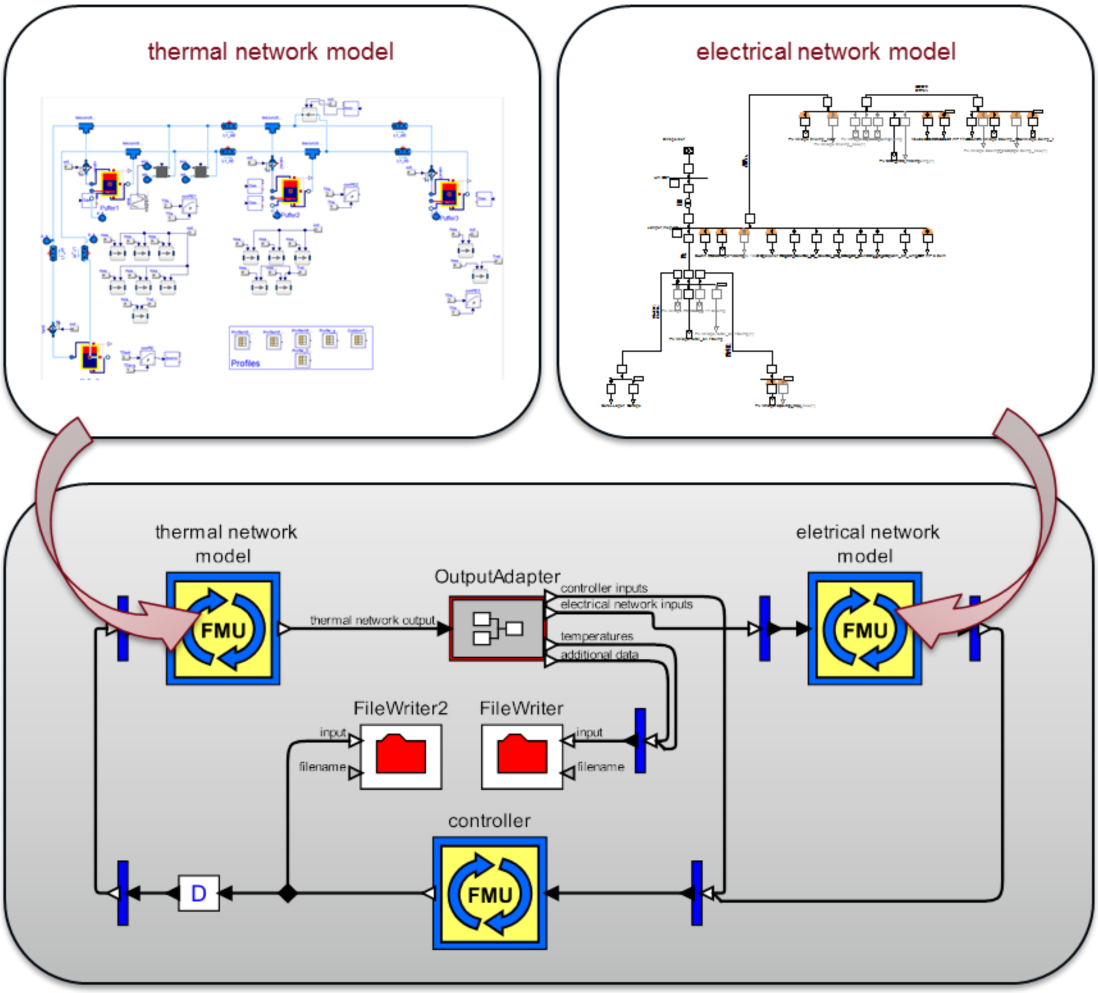


Figure 1: Graphical representation of a typical co-simulation model (bottom) and the detailed domain models (top).

3. Results for use case IKB Demonet

System configurations considered in the design process

For use case IKB Demonet only a limited number of realistic sizing options for the various components have been identified (compare with deliverable report D2.3). This led to a total of 6 potential system configurations (see Table 1), which differ in the sizing of the heat pumps and thermal buffers.

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="3">heat pumps</td></tr>
<tr><td>small size configuration
WWHP: 100 kW
GWHP: 50 kW</td><td>medium size configuration
WWHP: 150 kW
GWHP: 50 kW</td><td>large size configuration
WWHP: 200 kW
GWHP: 50 kW</td></tr>
<tr><td rowspan="2">thermal storages</td><td>small size configuration
RG 2: 15 m3,
RG 4: 25 m3</td><td>config1</td><td>config2</td><td>config3</td></tr>
<tr><td>large size configuration
RG 2: 20 m3,
RG 4: 30 m3</td><td>config4</td><td>config5</td><td>config6</td></tr>
</table>

Table 1: Overview of the system configurations.

Operational modes

As expected, the operational strategy is affected by the seasonal variations (temperature, solar irradiance), effectively resulting in seasonal operational modes.

Figure 2 and

Figure 3 show typical actuation patterns for the heat sources during different seasons. Each figure depicts the simulation results of roughly 3-4 days, where noontime of each day (or more precisely the time of day with highest solar irradiation levels) coincides with the actuation of the heat pumps (green and purple lines). These significant differences necessitate the evaluation of the system performance on a yearly basis, in order to provide a good basis for the choice of the optimal design.

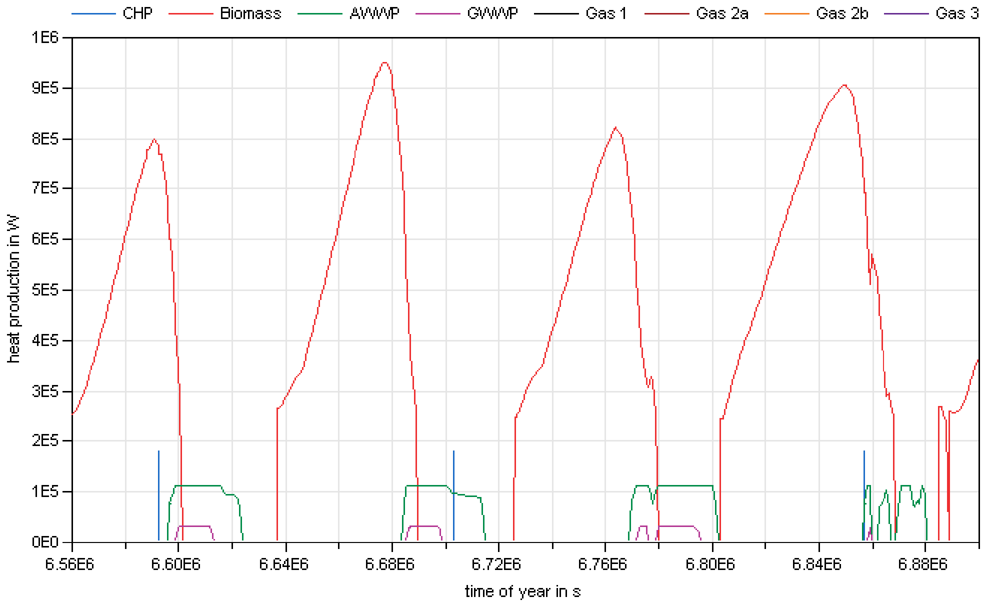


Figure 2: Typical actuation pattern of the different heat sources during transitional seasons (spring/autumn).

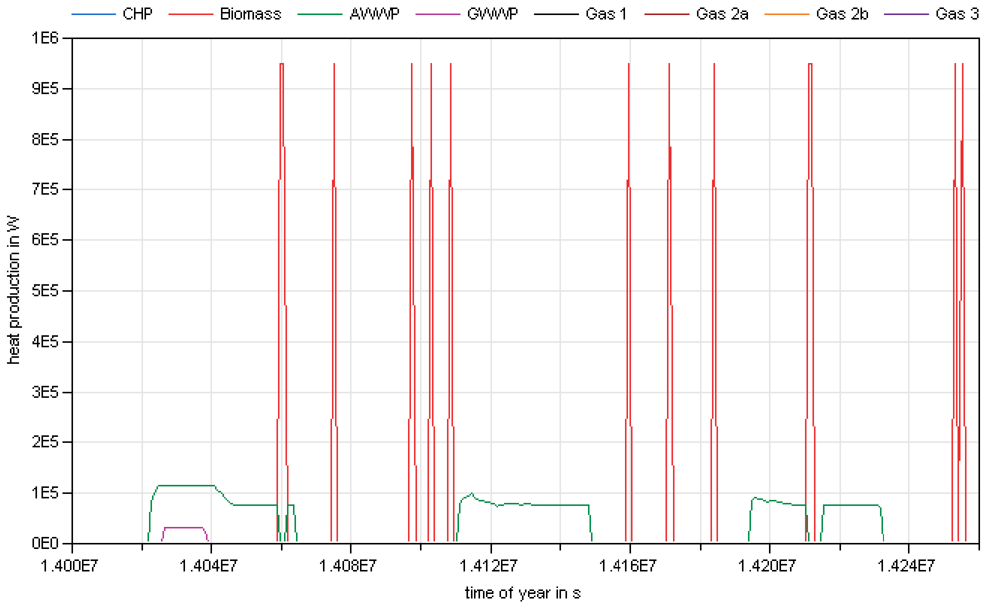


Figure 3: Typical actuation pattern of the different heat sources during summer

The figures show in some cases actuation patterns that would not be feasible in real-life operation, such as firing the biomass boiler for short periods of time. These effects can be considered as simulation artefacts caused by a simplified model of the process controls of the plants. However, the implications for the overall energy evaluation and optimal design are negligible. For instance, CHP and biomass operation for very short periods is not feasible due to increased operation and maintenance costs. In the real system such unfeasible actuation patterns could be easily avoided by using the gas boilers instead or allowing a reduced thermal storage temperature for short periods. However, for the overall system evaluation this makes no noticeable difference, since the associated energy flows are tiny compared to the overall consumption/production.

Optimization results

Heat pump sizes

Figure 4 shows the yearly energy production of the heat pumps for three different system configurations:

- small size configuration (100 kW th AWWP & 50 kW th GWWP) referred to as *config4*
- medium size configuration (150 kW th AWWP & 50 kW th GWWP) referred to as *config5*
- large size configuration (200 kW th AWWP & 50 kW th GWWP) referred to as *config6*

For all three cases the large size thermal buffer configuration (Roßaugasse 2: 20 m^3, Roßaugasse 4: 30 m^3) was used.

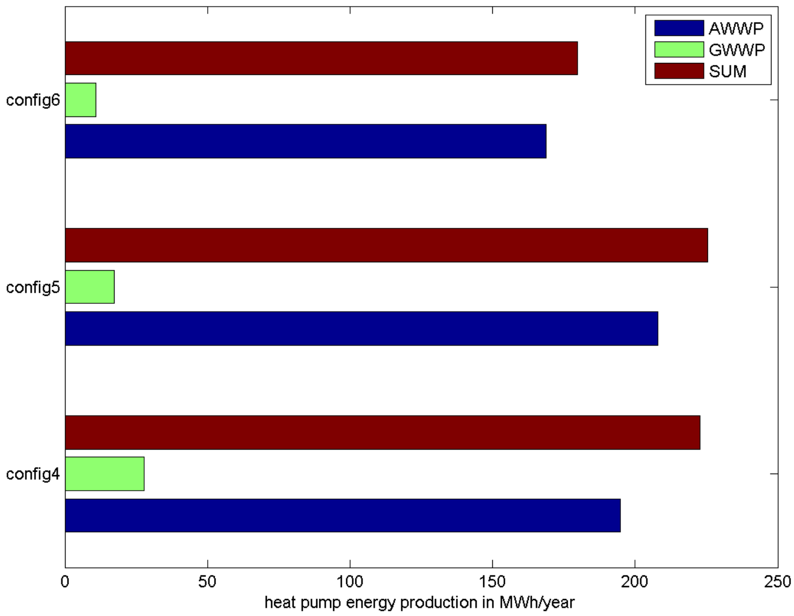


Figure 4: Yearly energy production of heat pumps.

The configuration with the largest waste water heat pump (*config6*) fails to exploit the full potential of the PV generation, due to its high operational threshold. Similarly, also the configuration with smallest heat pump (*config4*) fails to do so, due to its maximum electrical consumption. The medium size configuration (*config5*) provides in this regard the best compromise.

Thermal buffer sizes

In regard to the overall system performance (yearly energy production of plants, fuel consumption, etc.) the evaluation of the system configuration showed no considerable difference with respect to the sizing of the thermal buffers. However, the large size configuration for thermal buffers (Roßaugasse 2: 20 m^3, Roßaugasse 4: 30 m^3) requires less startups and actuation of the thermal plants. For instance, for the medium size heat pump configuration, the number of startups for the biomass plant is 10% higher when using small the size thermal buffer configuration.

Impact on fuel-based thermal plants

Figure 5 shows for the same system configurations the yearly energy production of the biomass plant (left) and the CHP (right). In the configuration with the large size heat pump (*config6*) the heat pump’s high operational threshold causes not only an increase of biomass-based generation, but actually leads to an overcompensation at the cost of the CHP-based thermal generation compared to the other configurations. In all three cases the thermal energy production of the gas boilers is around 230 MW/year.

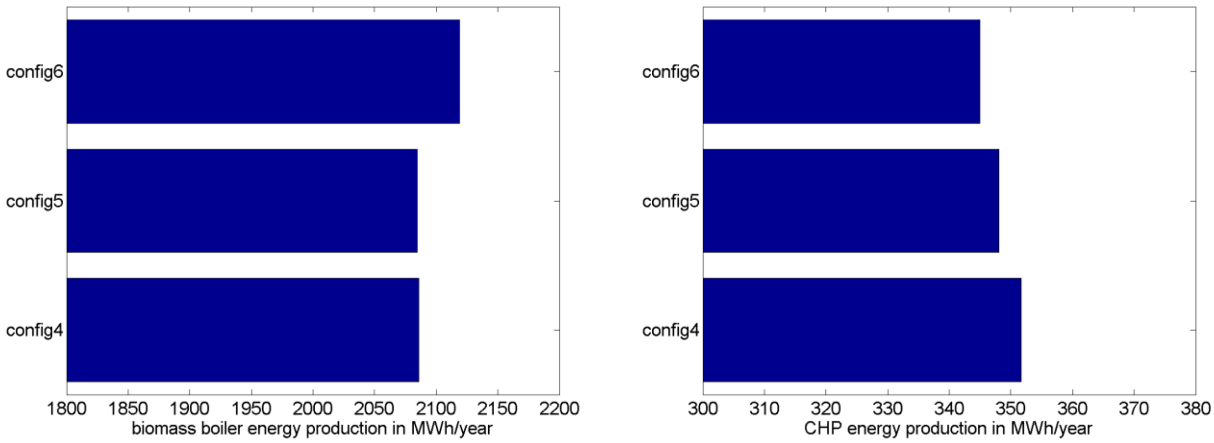


Figure 5: Yearly energy production for fuel-based thermal plants: the biomass plant (left) and the CHP (right).

In conclusion, even though the differences between the various configurations are rather modest, the configuration with the medium size heat pump (*config5*) shows overall the best thermal system performance.

Impact of the CHP

The proposed CHP size provides an effective reduction of gas boiler usage, see Figure 6, even though a complete shift away from gas boilers would require a much bigger CHP plant. Furthermore, the current design goal of minimizing on-site CO_2 emissions prevents an increase of operational hours due to the preference for the biomass boiler (compare with results for alternative operational strategy in Appendix below).

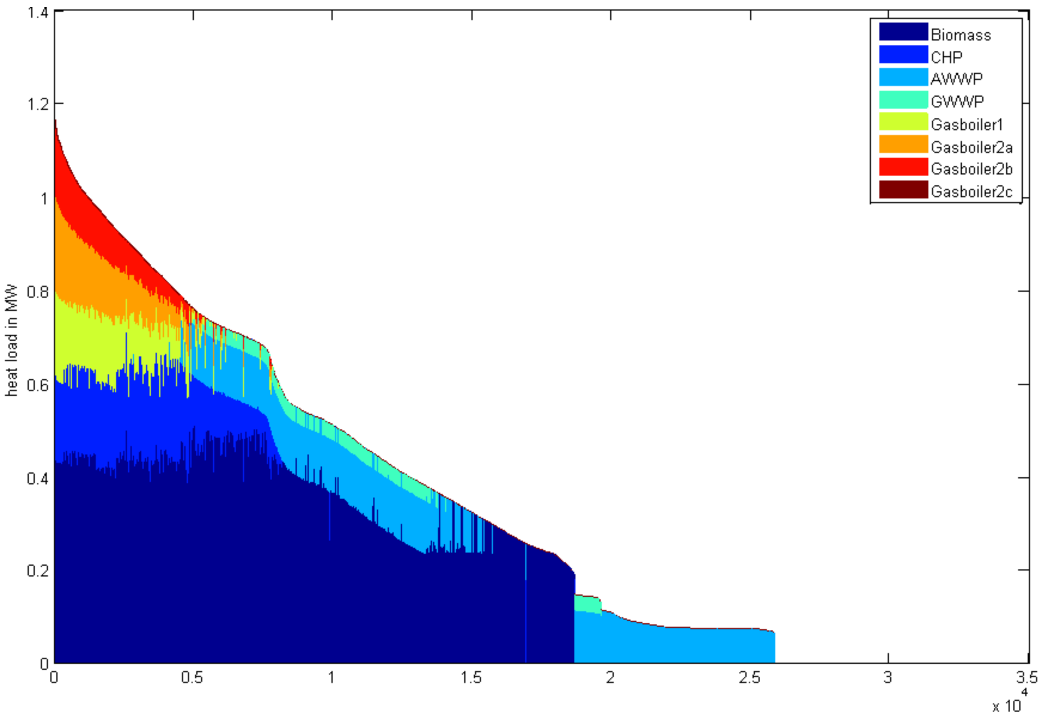


Figure 6: Load duration curve for system configuration *config5* (full year simulation).

Impact on the electrical network

Table 2 shows a comparison of the impact of the different system configurations on the electricity network with today's layout and the scenarios including the planned PV systems. All scenarios related to the system configurations related to the design process (*config1* to *config6*) include the planned PV systems. The table shows in the first column the scenario name and in the further columns:

- maximum transformer loading (*max. trafo loading*)

- maximum line loadings (*max. line loading*)
- duration of loading of lines over 70% (d*uration>70%*)
- voltage band usage (v*oltage band*)
- duration of the voltage band exceeding 10% (*duration*)

configuration	max. trafo loading	max. line loading	duration > 70%	voltage band	duration
today's layout	41.5%	92.6%	8.6%	5.25%	
new PV systems	41.8%	92.8%	8.6%	12.35%	3%
config1	42.2%	92.7%	8.62%	11.71%	0.96%
config2	43.7%	92.7%	8.62%	11.71%	0.9%
config3	43.8%	92.7%	8.62%	12.11%	1.3%
config4	42%	92.7%	8.62%	11.71%	0.94%
config5	43.7%	92.7%	8.62%	11.71%	0.9%
config6	43.8%	92.7%	8.62%	12.11%	1.3%

Table 2: Comparison of the impact on the electrical distribution grid.

Special consideration is given to the impact of system configuration *config5* on the electricity network and its elements. This configuration shows an improvement of the voltage band usage compared to the other scenarios when integrating the possible PV potential.

The following figures show a more detailed overview of the results of the electrical network simulation for system configuration *config5*. Figure 7 shows the transformer loading sorted in a descending order, followed by Figure 8, which shows the line loadings sorted in descending order. Figure 9 shows the node voltages over the course of one full year, followed by Figure 10, which shows the voltage band cumulative distribution.

Figure 11 shows the minimum and maximum voltage over the one year simulation period.

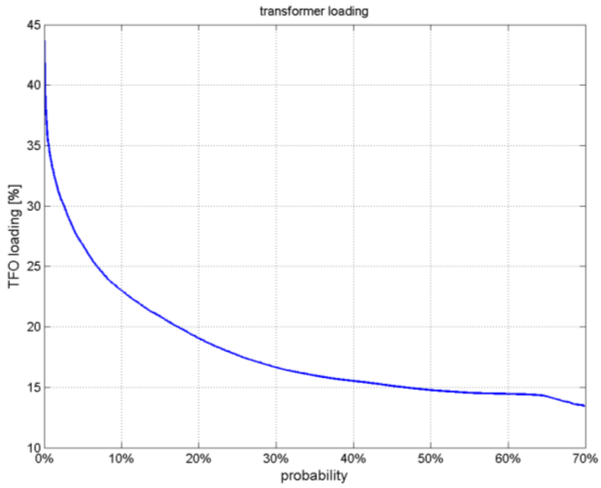


Figure 7: Transformer loading.

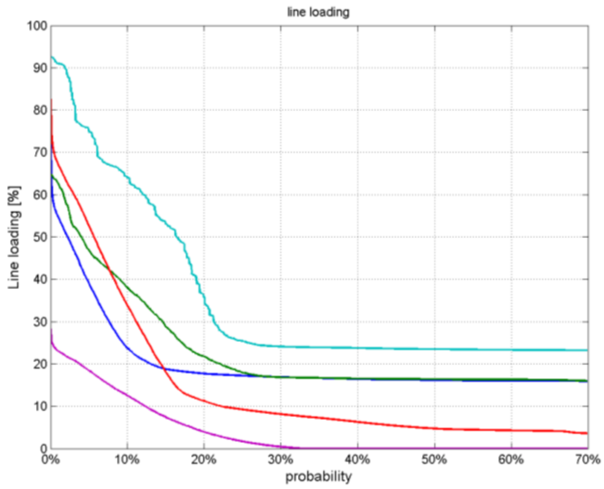


Figure 8: Line loadings.

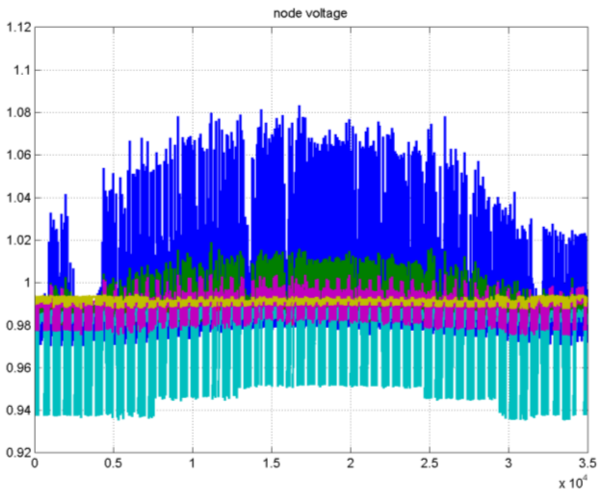


Figure 9: Node voltages for full year.

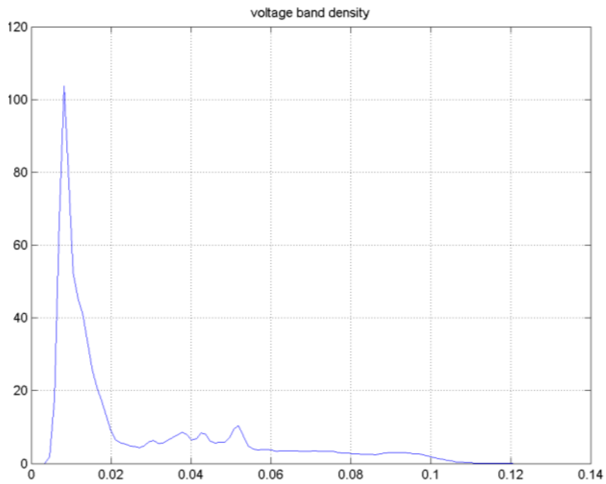


Figure 10: Voltage band cumulative distribution.

With a simulated maximum transformer loading of about 44%, the simulation indicates no problems at the transformer.

The maximum voltage band exceeds the 10% threshold up to 11.7% for about 0.9% of the whole simulation time (one year). Furthermore, one of the lines is overloaded (exceeding the 70% threshold) for about 8.6% of the simulation period (one year).

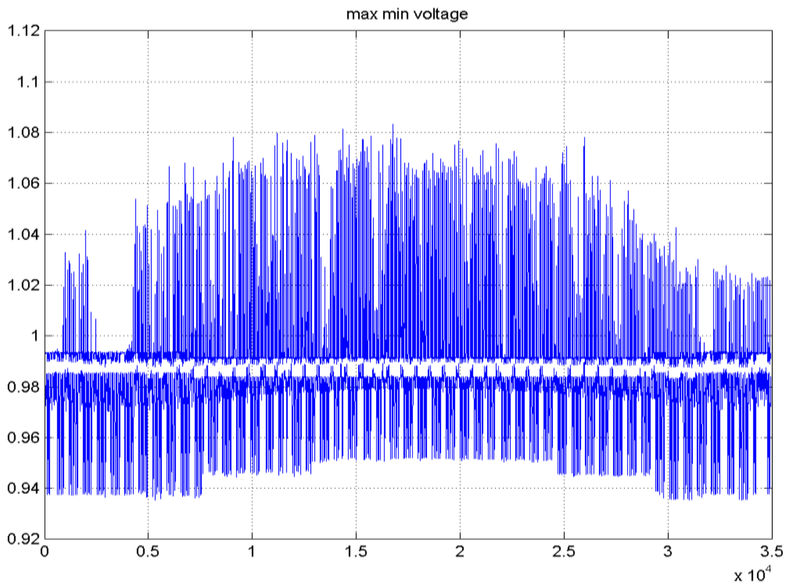
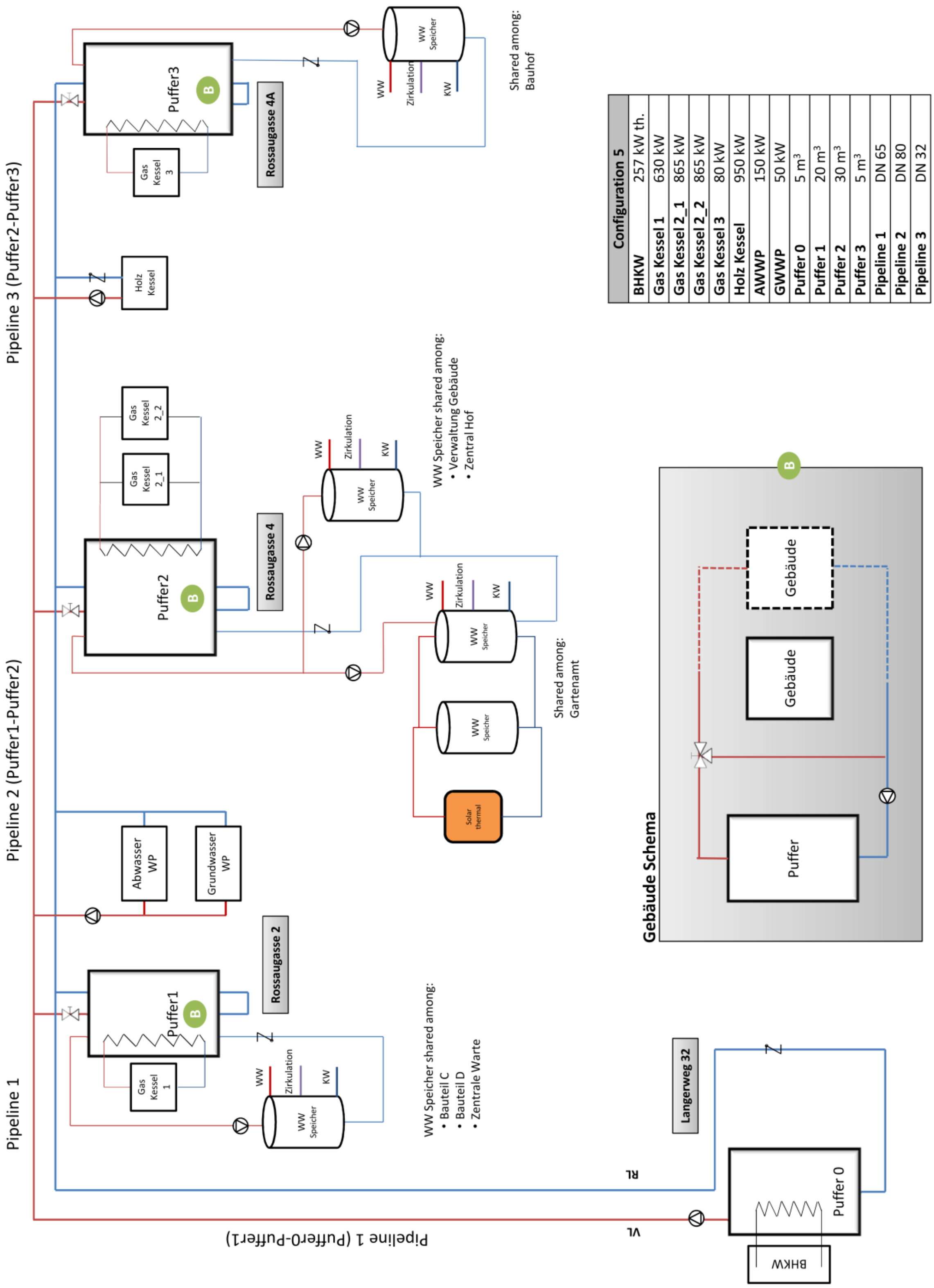


Figure 11: Minimal and maximal voltages for one year.

Conclusion

Even though the improvements from the system level point of view are limited due to the actual available PV generation and other practical constraints (e.g., economical aspects of CHP sizing), the system configuration with the large size thermal buffer layout (Roßaugasse 2: 20 m^3, Roßaugasse 4: 30 m^3) and the medium size heat pump layout (150 kW th AWWP & 50 kW th GWWP) can be clearly identified as the optimal system configuration. It optimally exploits the on-site PV generation while at the same time providing a modest reduction of fuel-based generation. Also, it has the most favorable impact on the electrical system. Figure 12 gives a schematic overview of this system configuration.



Configuration 5	
BHKW	257 kW th.
Gas Kessel 1	630 kW
Gas Kessel 2_1	865 kW
Gas Kessel 2_2	865 kW
Gas Kessel 3	80 kW
Holz Kessel	950 kW
AWWP	150 kW
GWWP	50 kW
Puffer 0	5 m³
Puffer 1	20 m³
Puffer 2	30 m³
Puffer 3	5 m³
Pipeline 1	DN 65
Pipeline 2	DN 80
Pipeline 3	DN 32

Figure 12: Schematic view of the optimal system configuration.

4. Results for use case Köstendorf

System configurations considered in the design process

For use case Köstendorf no predetermined choices regarding the sizes of components are available (compare with deliverable report D2.3), only lower and upper bounds were defined. Table 3 gives an overview of the degrees of freedom for the design and the associated lower/and upper bounds of their sizes.

component description	degree of freedom	lower limit	upper limit
heat pump 1	elec. power consumption	20 kW el	200 kW el
heat pump 2	elec. power consumption	20 kW el	200 kW el
heat pump 3	elec. power consumption	20 kW el	200 kW el
thermal storage 1	tank volume	20 m^3	50 m^3
thermal storage 2	tank volume	20 m^3	50 m^3
thermal storage 3	tank volume	20 m^3	50 m^3

Table 3: Degrees of freedom in the system design.

With 6 degrees of freedom (sizes of 3 heat pumps, sizes of 3 thermal storage tanks), the parameter search space is already quite large. For instance, even if there were just 3 possible heat pump sizes and 3 possible heat storage tank sizes, this would result in 729 possible system configurations.

For this reason, the metaheuristic optimization approach described in deliverable report D5.1 (Section 4) has been applied to optimize the system design. The optimization targets specified in in deliverable report D2.4 (Section 4) have been translated to a rule-based control strategy, whereas the overall goal of the metaheuristic optimization was the maximization of the thermal output from the storage tanks. The optimization comprised 15 iterations with a population size of 30, with each assessing the performance of a half-year simulation run.

Optimization results

Optimal system configuration

Table 1 summarizes the optimal system configuration for the use case Köstendorf according to the metaheuristic optimization procedure and the according operating times at nominal capacity for the heat pumps (relative to the overall simulation time).

component description	degree of freedom	optimal value	operation at nominal capacity
heat pump 1	elec. power consumption	29,9 kW el	7,8%
heat pump 2	elec. power consumption	91,2 kW el	8,1%
heat pump 3	elec. power consumption	198,9 kW el	4,9%
thermal storage 1	tank volume	41,2 m^3	--
thermal storage 2	tank volume	36,1 m^3	--
thermal storage 3	tank volume	35,7 m^3	--

Table 4: Optimization results for use case Köstendorf.

Impact on the thermal network

The total PV overproduction in the considered period of time (half year) is around 140 MWh el. Given a total demand of thermal energy of 3,9 GWh th in the same period of time, the theoretical maximum for reducing the thermal plant reduction is around 7% (assuming an effective conversion factor of 2).

Figure 13 shows the associated heat load duration curve for the half-year simulation period (please note the logarithmic scaling of the ordinate axis). Figure 14 shows how the thermal energy discharged from the thermal storages contributed to the total energy mix. As can be concluded from the figure, even in the optimal configuration the plant production can only be reduced by around 4,3%. Also, the heat pumps can rarely be operated. However, during warm periods the heat pumps are able to cover around 25% of the total thermal demand, see Figure 15.

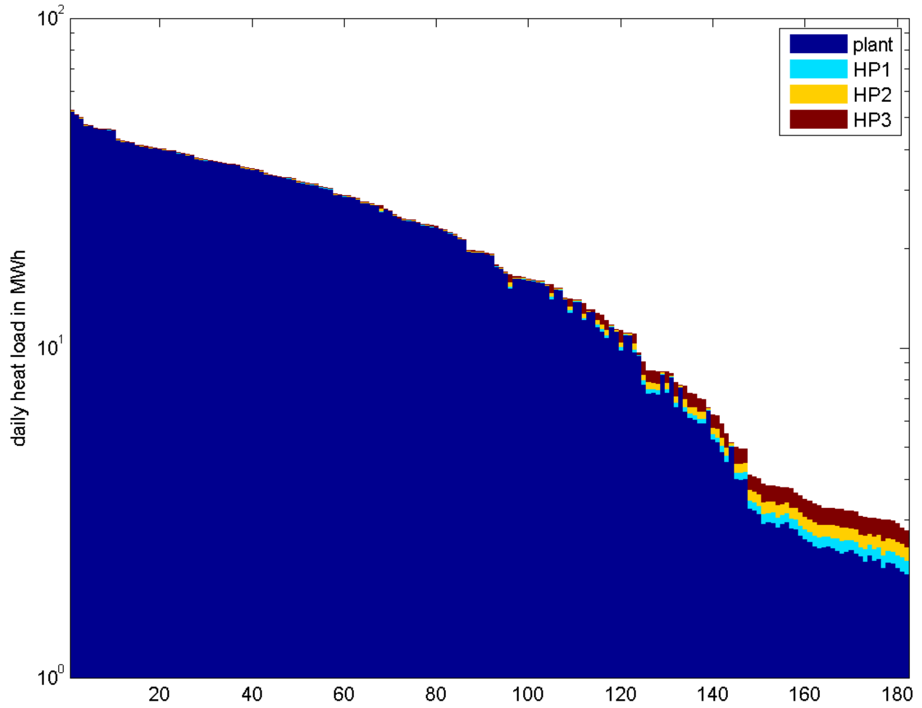


Figure 13: Daily heat load duration curve for the optimal system configuration (half year simulation).

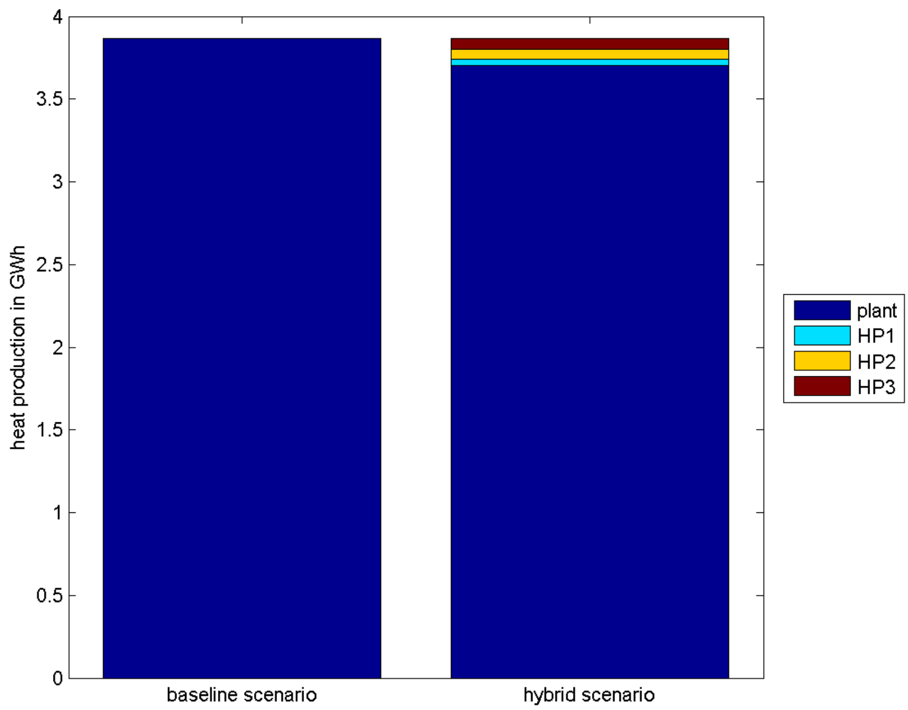


Figure 14: Comparison of heat production for baseline and hybrid scenario (half year simulation).

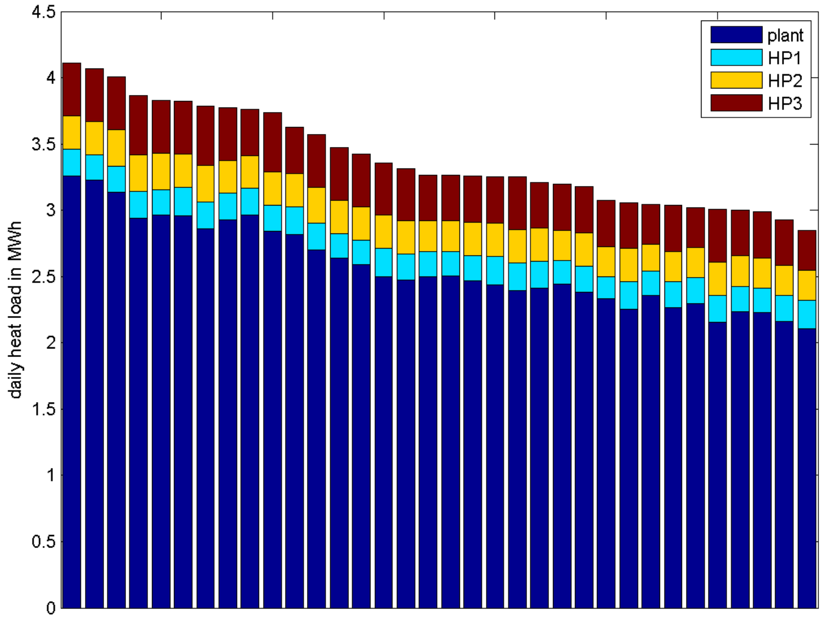


Figure 15: Daily heat load duration curves of warmest days (half year simulation).

Impact on the electrical network

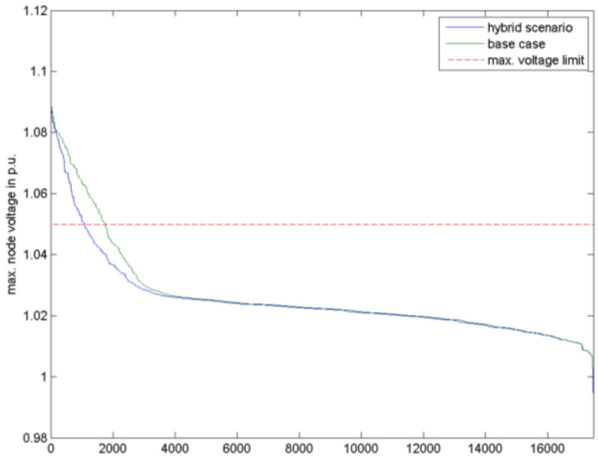


Figure 16: Distribution of maximum node voltages for each simulation step at critical nodes.

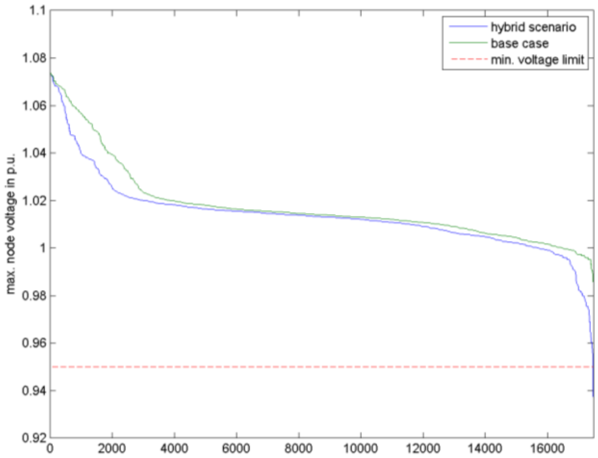


Figure 17: Distribution of minimum node voltages for each simulation step at critical nodes.

Figure 16 shows the distribution of the maximum node voltage at each simulation time step for the critical network nodes, comparing the baseline scenario with the hybrid scenario. As can be seen, even though the hybrid approach by itself is not able mitigate the problem of overvoltage, it is very well capable of reducing it. At the same time, even though it lowers the minimum node voltage of the critical nodes, it does in general not violate the lower threshold.

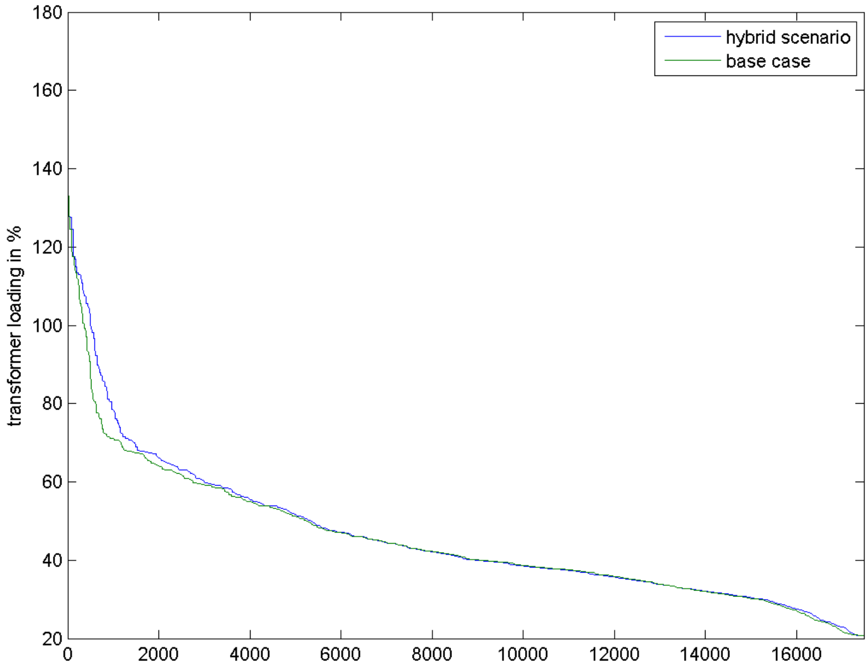


Figure 18: Distribution of transformer loadings.

Figure 18 shows the distribution of the transformer loading for each simulation time step, comparing the baseline scenario with the hybrid scenario. As can be seen, the same control strategy reducing the stress on the network caused by overvoltage is not able to reduce the stress on the transformer, but actually worsens the situation little bit.

Conclusion

Even though the improvements from the system level point of view are limited due to the actual available PV overproduction, the optimal system configuration (according to the metaheuristic approach) clearly aids the operation of both the thermal and the electrical network.

5. Conclusions

The methods and tool developed for and used in the OptHySys project are very well suited to analyze hybrid thermal-electrical energy systems and to optimize the associated system design. Two complementary approaches have been introduced have been successfully deployed to two different use cases.

Given the focus of both use cases on the local utilization of PV (over)production, the actual improvement gained from the hybrid operation is limited in both cases. Clearly, additional sources of (renewable) electrical energy are necessary to have a more pronounced impact on both the electrical and the thermal domain. Possible sources are large-scale PV or wind generation or through participation in an energy balancing market.