

D3.2 Thermal Building Model

Final Version

Deliverable

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ABOUT THE NEMoGRID PROJECT

The NEMoGrid Project is mainly focused on the definition of innovative business models that could ease the penetration of renewables into the distribution grid, with a particular emphasis on the definition of a peer-to-peer strategy based on the blockchain technology. The new business models will encourage the active participation of citizens and the assumption of their new role of prosumers, by allowing them to enter new markets as players. Among the tested scenarios, the most innovative one will be based on a peer-to-peer market. In this case, new decentralized platforms based on the blockchain technology will allow zero marginal cost transactions. In order to test the new business models effectiveness, a simulation framework will be developed. Each scenario will be evaluated base on a number of KPIs. Existing demo sites in Lugaggia (CH), Björklinge (SE) and Wüstenrot (DE) will be used to validate the business model that gives the best simulation results. Real loads will be controlled by the algorithms developed in the simulation phase. Technical developments within NEMoGrid will be supported with user research, gathering empirical data on prosumers decisions and interactions. The results will be used to develop an adoption model and to continuously refine the simulations.

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1. MODEL DESCRIPTION

The Thermal Building Model is used to estimate the thermal building energy demand and the time-dependent indoor building temperature depending on heating input and weather. Furthermore, various components are implemented to allow a complete building simulation e.g. a thermal storage and heat pump. The building simulation is implemented in Python and leverages EnergyPlus [01] as a building simulation framework.

Building Model

The building model is based on a reference building which can be adopted to different simulation scenarios. The heating demand for example can be adapted by changing the building energy standard, or changing the building's orientation, which affects solar gains. In the next two chapters the building, as well as its classification within energy standards will be described.

1.1. REFERENCE BUILDING

As a reference building, a single-family house with a usable building area of 179.5 m² is used. The usable area of the building is in the range of a typical single-family house for plant simulations in Europe. The enveloping surface is 416.8 m², the gross building volume 561 m³. The enveloping surface and the gross - building volume is calculated using the external dimensions of the reference building. The usable floor space is calculated depending on the building volume. In addition, it is assumed that the building floor slab is attached to an unheated basement. The attic is not included in the heated area. The building is considered to be unshaded and no sun protection is provided.

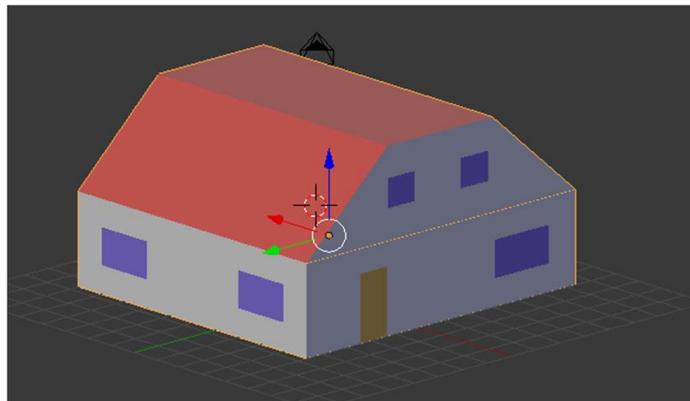


Figure 1 The reference building of the simulation.

Building Classification

To generate a set of typical single-family households that are present in distribution grids, the building standards of a typical German village is evaluated. The differentiation of the different building classes was made according to the respective building standards of the German energy saving regulation [02]. These building standards set for houses, built in

the period of the respective valid regulation, the maximum permissible coefficients and material properties of the materials to be used. From this, the maximum permissible specific annual heating requirements can be derived. The classification in building classes was made according to the year of construction and maximum values for annual heating requirements. An advantage of the subdivision according to these years or the respective adaptations of the regulations are the more or less equal intervals between the individual regulations. With this information the respective distribution of building models can be generated. In *Figure 2* the resulting distribution is shown.

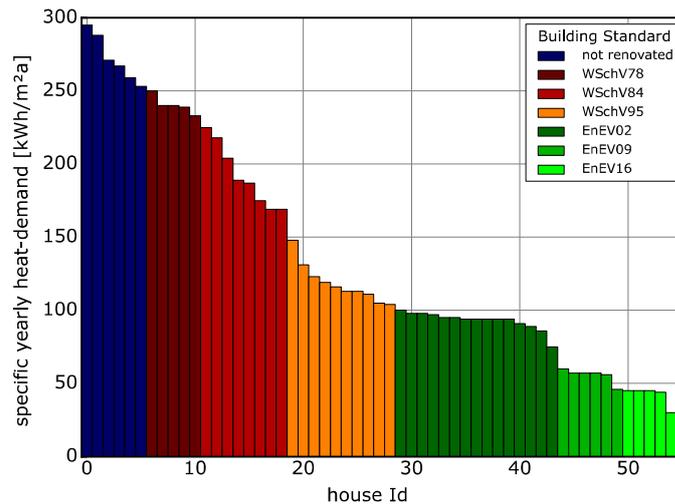


Figure 2 Distribution of the yearly heat demand over the different buildings.

Building model in simulation framework

Due to its versatility, simplicity in characterization, and computational speed, the final thermal household has been modeled as a single-state RC equivalent circuit (depicted in *Figure 3*), directly in Python. This allows running simulations with several buildings in a reasonable amount of time and capturing with sufficient detail the thermal behavior of a building. In this simplified model, a building is characterized by three main parameters:

- The thermal capacity of the building C_{th} (J/K)
- The thermal resistance of the building R_{th} (K/W)
- The total area of the windows A_w (m²)

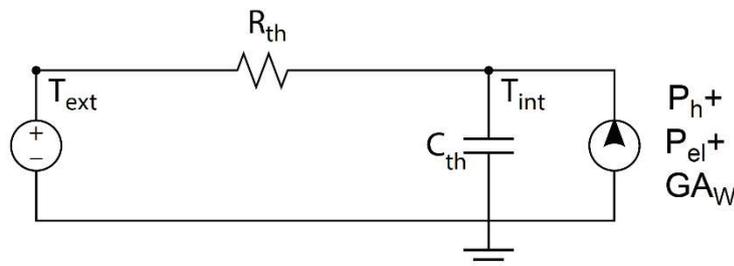


Figure 3: 1R1C model of building used in simulations. R_{th} : thermal resistance, C_{th} : thermal capacity, T_{int} : internal temperature, T_{ext} : external temperature, P_{el} : thermal power from the heating system, P_h : thermal power from occupants, GA_w : solar gains.

1.2. AUXILIARY COMPONENTS

In this chapter, the additional components of the simulation framework are described regarding their technical details and implementation.

Heat Pump

A heat pump is a device that converts heat at low temperature into heat at higher temperature using electrical energy. The efficiency of a heat pump is described by the coefficient of performance (COP) which is the ratio between output heat energy and input energy:

$$COP = \frac{\dot{Q}}{P} \quad (1)$$

The output energy \dot{Q} is the heat flux at high temperature whereby the input energy P is the electrical power required to operate the heat pump. Since the heat that the heat pump harvests from the environment is not considered as input power, the COP is higher than 1. With regard to heat pumps, a distinction is made depending on the environment the ambient heat is taken from. Within this project ground source heat pumps (GSHP) and air source heat pumps (ASHP) are considered. The COP for the ideal reversible thermodynamic heat pump process is described by

$$COP^{carnot} = \frac{1}{\eta^{carnot}} \quad (2)$$

where η^{carnot} represents the carnot efficiency

$$\eta^{carnot} = 1 - \frac{T_{source}}{T_{sink}} \quad (3)$$

with T_{source} and T_{sink} representing source and sink temperature respectively. Different approaches to model the behavior of heat pumps such as dynamic thermodynamic models [03] and steady-state black-box-models [04] are applied. As the focus of this project is not only on heat pumps but on cross-sectoral energy systems a quasi-steady-state model is considered as in [05]. The efficiency of the heat pump COP^{HP} is modeled by the following equation

$$COP^{HP} = COP^{fl}(T_{source}, T_{sink}) \cdot PLF(PLR) \quad (4)$$

where COP^{fl} represents the efficiency at full load and PLF the partial load factor as a function of the partial load ratio PLR . In order to model COP^{fl} two approaches are implemented. As a reference, a quadratic regression model applied on manufacturer data to describe COP^{fl} is taken from [06]. The model equations for ASHP and GSHP are

$$COP^{fl} = 6.08 - 0.09 \cdot \Delta T + 0.0005 \cdot \Delta T^2, \quad (ASHP) \quad (5)$$

$$COP^{fl} = 10.29 - 0.21 \cdot \Delta T + 0.0012 \cdot \Delta T^2, \text{ (GSHP)} \tag{6}$$

A second approach applies temperature dependency from (2) and (3) to a reference efficiency COP^{ref} at reference temperature conditions T_{source}^{ref} and T_{sink}^{ref} . In this approach the COP^{fl} at full load is described as followed

$$COP^{fl} = \frac{COP^{ref}}{COP^{carnot}(T_{source}^{ref}, T_{sink}^{ref})} \cdot COP^{carnot}(T_{source}, T_{sink}) \tag{7}$$

The comparison of the two approaches for ASHP and GSHP is shown in *Figure 4*.

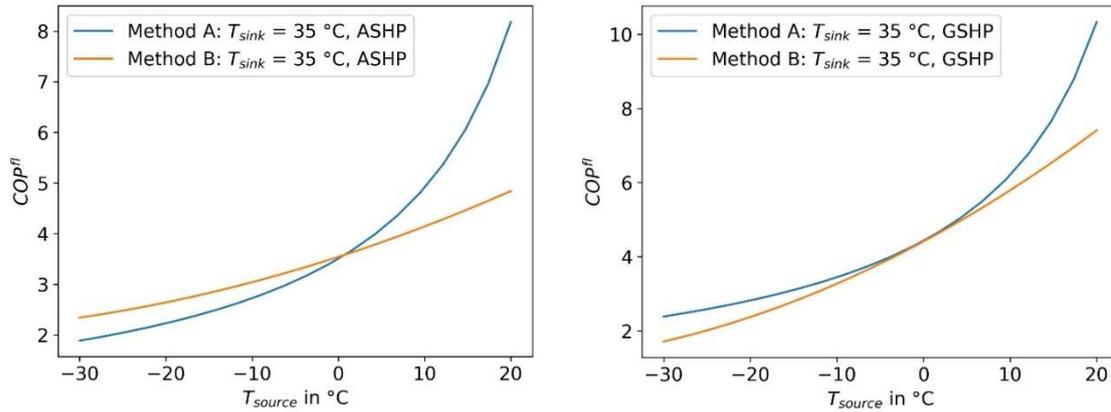


Figure 4 Comparison between model with carnot efficiency (method A, Eq. (2) and (3)) and quadratic regression model applied on manufacturer data from [6] (method B, Eq. (6) and (7)) for ASHP (left) and GSHP (right).

The part-load behavior of the heat pump is obtained from simulation results realized with software framework TESpy [07]. *Figure 5* shows the resulting curve of *PLF* over *PLR*.

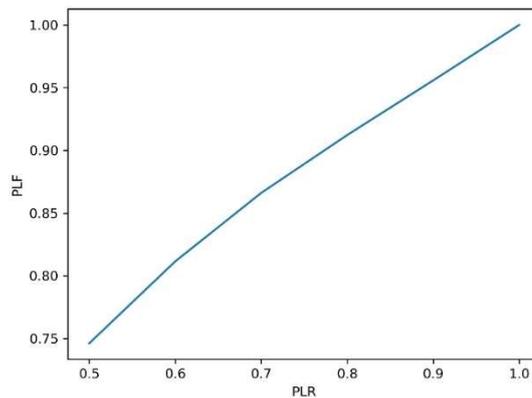


Figure 5 Partial load factor (PLF) over partial load ratio (PLR).

Ground Model

To model the efficiency of brine/water heat pumps, the ground temperature has to be estimated at installation depth of the earth collectors. As the drinking water pipes are also laid in the ground, the inlet temperature of the drinking water can also be estimated with

the ground temperature. The soil is modeled according to the semi-infinite body model [08].

The principle of this model is that the the temperature of the earth at high distances from the borehole pipes is considered constant. For soil, this can be estimated with the average yearly temperature, as the near-surface temperature is mainly influenced by the air temperature if geothermal effects are neglected. A time offset is also taken into account for the soil temperatures. According to [09], this is approx. 24 days per meter of soil depth. For a depth of 0.8 m results in an offset of approx. 19 days, for 1.5 m depth 36 days. In Figure 6 the soil temperatures for two depths are displayed. It can be seen that the annual average temperature is approximately the same as the annual average temperature for the depth of the earth collector, but is still subject to slight seasonal fluctuations.

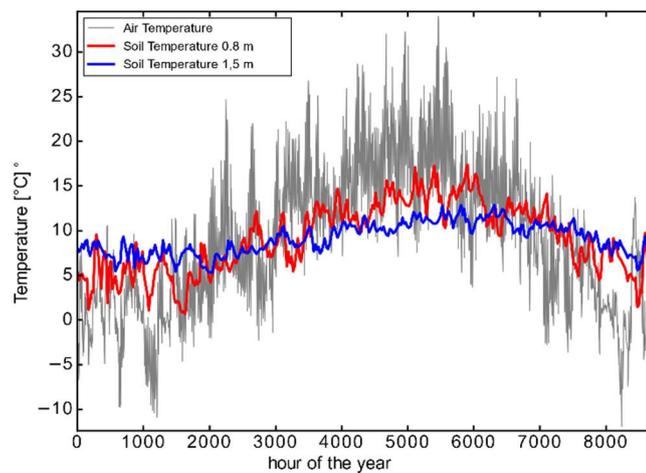


Figure 6 Plot of the soil and air temperature over the course of one year.

Thermal Storage

ZSW model:

The Thermal Energy Storage is implemented as a stratified storage tank. It includes buoyancy, heat transfer, heat losses and mixing losses according to [10]. It differs in the charging and discharging process: It is assumed that the tank is charged with only minor disturbance in the stratification. Therefore heat is introduced and removed from the top layer while fresh water or heating return is fed in at the bottom layer. In Figure 7 the temperature stratification is displayed at the beginning of the simulation and after one charge and discharge cycle.

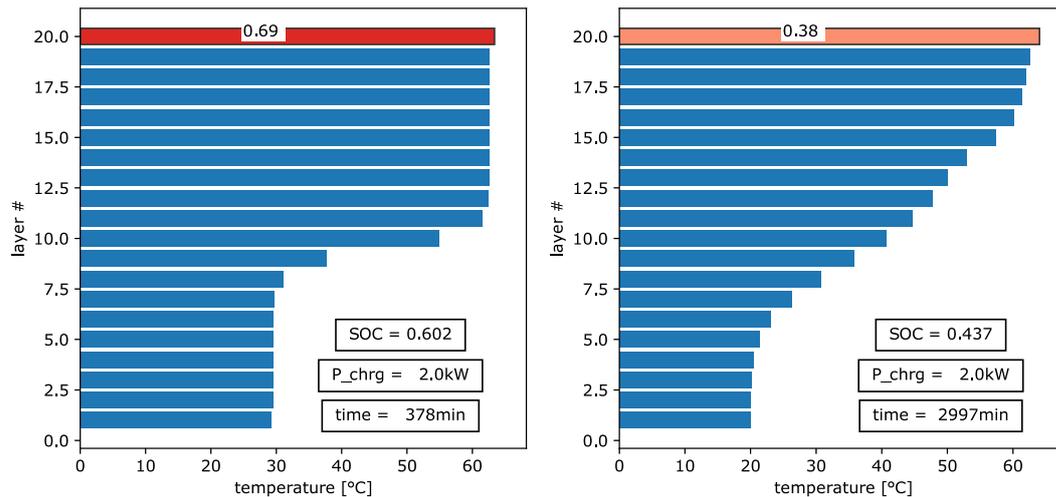


Figure 7 Plot of the temperature distribution within the water tank at the beginning of the simulation (left) and after one full charge and discharge cycle.

SUPSI model:

SUPSI in parallel developed a model that uses a fixed number of perfectly mixed layers, in which the temperature is considered to be uniform. This nodal approach is widely used in energy simulation tools. The main considered heat transfer phenomena are the following:

- Conductive and convective heat transfer between the heat source and the water
- Conductive heat transfer between water layers
- Additional heat transfer due to conduction in the tank metal layer
- Convective heat transfer between tank and environment
- Buoyancy-driven convective effects

The model, originally presented in [11], was entirely rewritten in Python and validated against Polysun.

2. IMPLEMENTATION

2.1. ENERGYPLUS

EnergyPlus is a free, open source, and cross-plattform complete building energy simulation program. It can be used to model various aspects of building energy consumption, such as heating, cooling, ventilation, lighting or socket and process loads. Its development is funded by the Building Technologies Office (BTO) of the U.S. Department of Energy (DOE). It is used in the simulation to simulate the thermal energy balances of the buildings. It offers complex and accurate simulation algorithms which have been verified multiple times in literature. [12]-[14]

FMU and Python Binding

The Functional Mock-up Interface (FMI) defines a standardized interface that can be used to link different simulation software. The idea behind FMI is this: If the real product is made up of a multitude of components that interact in a complex way and are controlled by a number of complex physical laws, then it should also be possible to create a virtual product consisting of a number of different physical (software) models. The FMI framework is used to connect EnergyPlus to the python simulation framework. To do this the EnergyPlus instance has to be exported to a so called Functional Mockup unit. This is done with the *EnergyPlusToFMU* tool [15] and the included within the simulation environment using *PyFMI* [16].

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