Predictive and flexible system controller for hybrid power supply systems

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Abstract. Regarding the overall efficiency of hybrid power supply systems, a system controller as an addition to device controllers was developed to contribute to its increase. An essential premise in the development of such a controller was the modular structure and the implementation as an open source solution. By using the MQTT protocol, the controller can operate within an IoT-network and hence be used universally, e.g. in a Software- (SiL) or in the Hardware-in-the-loop (HiL) environment as well as in field test. In order to make optimal use of the flexibilities provided by thermal or electrical storages, MPC (Modell Predictive Control) functionalities were implemented in the controller, which, however, are supported by rule-based algorithms on a "fallback level". The target values of the control can be adjusted variably and include economical as well as ecological aspects in a weighted way. The open structure of the controller makes it possible to easily include other system components in the control concept and also to operate the controller either locally, in an edge device or in a cloud environment. The performance of the controller was demonstrated by SiL- and HiL-tests. Here, annual characteristic values were determined on the basis of representative days. The representative days were selected using a cluster procedure. Overall, energy and cost savings can be demonstrated by using the controller, which are particularly effective in the optimized use of electricity from photovoltaic systems in combination with heat pumps.

Keywords hybrid energy systems, heat pump systems, sector coupling, renewable energies, carbon footprint, model predictive control.
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1. Introduction

Driven by efforts to save energy and decarbonize the building sector, hybrid systems for supplying energy to buildings are becoming increasingly important [1]. Here, generators using fossil fuels or heat pumps are often combined with renewable energies. A central system controller or energy manager is required to ensure that the individual components, which are often highly developed, also achieve high energy efficiency values in the overall system. Particularly noteworthy in this context is the possibility of combining diverse components from different manufacturers into a complex energy system and supporting the sector coupling between electricity and heat. For the improvement of the self-consumption share and economic efficiency of photovoltaic systems, energy management systems with predictive features are beneficial. In a research project, a cross-platform system controller was therefore developed and tested in a Software-in-the-loop (SiL) and further in a Hardware-in-the-loop (HiL) environment. The procedure using HiL and SiL investigations was pre-developed and successfully tested in previous research projects [2], [3], [4], [5], [6]. An essential premise in the development of the controller is the use of an open source software structure, which, due to its modular design and the use of the MQTT protocol, allows a rapid adaptation to a wide range of energy systems. This approach distinguishes the controller from other state-of-the-art solutions, which are partly proprietary or have been strongly adapted to specific energy systems. With regard to the energy management functions, MPC algorithms allow the utilisation of further savings potentials compared to rule-based functions [7]. Thus, MPC functions were implemented for a setup with a thermal and an electrical storage. The following article presents the software architecture of the controller and the description of selected services. In addition, a use case is described in the article and economical and ecological effects of the controller operation are shown and discussed.

2. Architecture of the controller

2.1 Fundamental consideration

Python was chosen as the programming language for the development of the platform controller. To ensure a stable workaround (interpreter, package versions, etc.), poetry [8] is also used, where corresponding requirements are defined and the system controller can be executed in a virtual environment. The MQTT protocol [9] is used for the machine-to-machine (M2M) data transfer, which means that network access is a minimum requirement for using the system controller. MQTT is considered a standard protocol in the IoT sector and is particularly suitable for the data transport of telemetry data, such as sensor values, etc.

In the context of the project, MQTT is used via TCP (transmission control protocol). The quality of service (QoS) is set to zero, i.e. each message is sent at most once. The QoS is adjustable if a higher reliability of the data transport is required. The possible QoS are:

- QoS = 0: The message is sent at most once
- QoS = 1: The message is sent at least once
- QoS = 2: The message is sent exactly once.

The message broker (server) used is Eclipse Mosquitto [10], which is available as open source software. There exist many alternatives and it could also be replaced by cloud solutions, for instance. In the context of the project, the “localhost” as a broker address is used, i.e. the end device on which the platform controller is executed also serves as a broker.

The system controller thus represents a client in the client-server structure of MQTT and communicates with all system components that are also MQTT-capable. If no MQTT interface is available, it is conceivable to upgrade the component (e. g. through MQTT gateways), which can convert the MQTT messages into any signals (e. g. serial communication standards as RS-485). Due to the broad application of MQTT in the IoT area, various gateways are already established on the market.

2.2 Structure of the system controller

The system controller has a modular structure and is supplemented by corresponding scripts as functions are expanded. According to Fig. 1, each component of the real plant system is mapped as a separate client in the platform controller and is both publisher (source) and subscriber (sink).

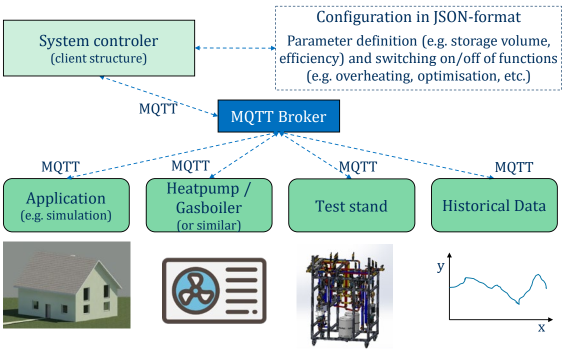


Fig. 1 – Structure of the system under consideration

The individual clients are configured via configuration files in JSON format. Each client is assigned to a specific JSON file (client-JSON pair). Within the configuration files, a unique assignment of parameters and their values ('key-value' assignment) is made, which can be adapted to the desired system. On the one hand, these can be constant parameters, such as a nominal power. On the other hand, the assignment can be to a specific address (topic) through which the clients send or receive their (transient) measured values to or from the broker in real time.

The heart of the system controller is an energy manager to which all measured and calculated values of the clients are transferred. Based on these values, rule-based decisions are made here. Depending on the configuration, the energy manager decides, among others, whether to switch-on the energy converters in a hybrid system, whether to feed-in or charge a battery using photovoltaic yield, and whether to switch between heating and cooling mode using heat pumps with cooling function. An overview of the decisions about switching-on the energy converters in the current project is provided in the Fig. 2.

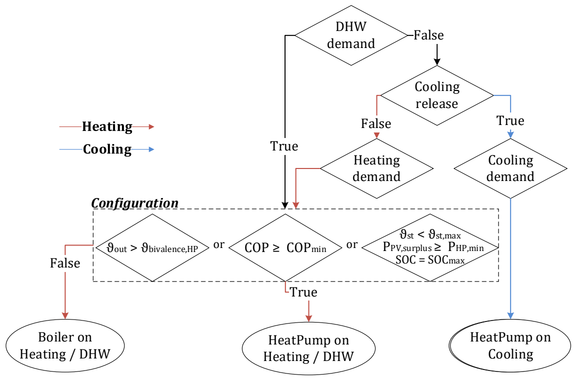


Fig. 2 – Decision tree of the energy manager

If part of the energy system, a photovoltaic system can be taken into account while deciding whether an electrically driven heat pump or an electric heating element is to be preferred. Moreover, the system controller provides an overheating function to heat up thermal storages using photovoltaic yield while there is no heating demand. For this purpose, energy characteristics of the appliances, status information of the thermal storage units as well as a weather forecast must be taken into account for the prediction of the heat pump efficiency. As mentioned, it is necessary that the components are MQTT-capable for this. Each of the components is configured as a controller client in the platform controller and can be added via TRUE/FALSE assignments in the energy manager (see Fig. 3).

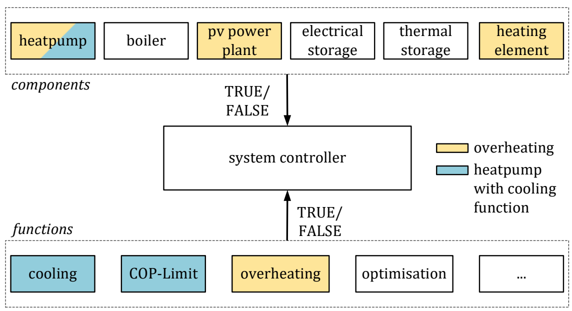


Fig. 3 – Possible assignments of the system controller

2.3 Model Predictive Control (MPC) algorithm

For the MPC control function, forecast data of the weather, energy generator and the PV yield are necessary. Within the project, the forecast values are, among others, determined both from measured data using regression and from known annual load and yield profiles. The last mentioned is thus considered as a perfect forecast and essential for determining the maximum possible benefit. For determining the forecasts from historical data and in addition to the implementation of appropriate measuring equipment, a data storage function must be implemented, which saves historical data on a sliding basis over a certain period of time (e.g. the last 72 hours). A snapshot is provided by the Fig. 4. Fine-tuning or improving forecasting functions is not intended to be part of this project. In the system controller, the possibility of both reading profiles and determining the forecasts based on historical data are implemented and can be selected accordingly.

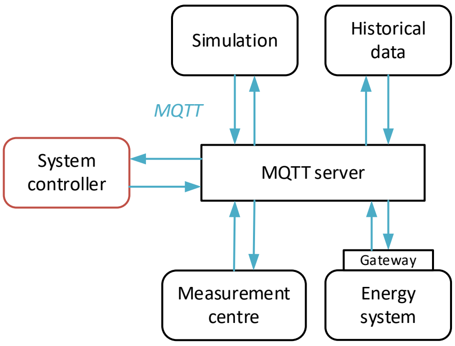


Fig. 4 – Basic communication structure of the system

The forecasts are determined for the following parameters:

- Heating/Cooling energy demand
- Energy demand for domestic hot water
- Electrical energy demand of the single-family house (without energy supply)
- Photovoltaic output
- Outside temperature (for determining COP/EER for heatpump)

The *heating energy demand* forecast is a form of trend forecast using linear regression. The method was used and validated in multiple studies [11], [12], [13]. The basis of the trend procedure is historical data of the heating load and the outdoor temperature ($Q_{i,j}$ and $\vartheta_{a,i,j}$ respectively) based on 72 hours (≙n=3 days). The heating energy demand for the next timestep Q_{i+1} is calculated according to the equations (1) to (3).

$$Q_{i+1} = m_i \cdot \vartheta_{a,i+1} + t_i \quad (1)$$

with

$$m_i = \frac{\sum_{j=0}^{n}(\vartheta_{a,i,j} - \bar{\vartheta}_{a,i}) \cdot (Q_{i,j} - \bar{Q}_i)}{\sum_{j=0}^{n}(\vartheta_{a,i,j} - \bar{\vartheta}_{a,i})^2} \quad (2)$$

$$t_i = \bar{Q}_i - m_i \cdot \bar{\vartheta}_{a,i} \quad (3)$$

Within the scope of the project, an annual load profile of a single-family house is used to enable a perfect forecast for the *electrical energy demand.* If no profile is available, the average value of the last few days at the respective time can be determined and used as an alternative. In the mean value procedure, weekdays are not taken into account, as otherwise a large amount of historical data would be required.

The *photovoltaic output* is determined either via the persistence method using a "clear-sky" factor or via an annual load profile. In the scope of the project, an annual load profile was used. The persistence method is presented as follows: A clear-sky factor $f_{sky,i}$ is determined from the ratio of the instantaneous value $W_{PV,i}$ to the maximum photovoltaic yield $max(W_{PV,j})$ of the historically considered time, see equation (4).

$$f_{sky,i} = \frac{W_{PV,i}}{\max(W_{PV,j})} \quad (4)$$

The clear-sky factor is then used to determine the photovoltaic output forecast for the next timestep, see equation (5).

$$W_{PV,i+1} = W_{PV,i} \cdot f_{sky,i} \quad (5)$$

3. Case study

3.1 Use cases

For the simulation investigations and as software within the coupling in the HiL test, the numerical simulation programme (TRNSYS-TUD) [14] is used. This is a comprehensively revised and expanded program version of the commercial simulation program TRNSYS. The reliability of the source code has been extensively tested in numerous studies [14], [15], [16].

Building under consideration

The project examines a single-family building with an underfloor heating system in TRNSYS-TUD (see Fig. 5).

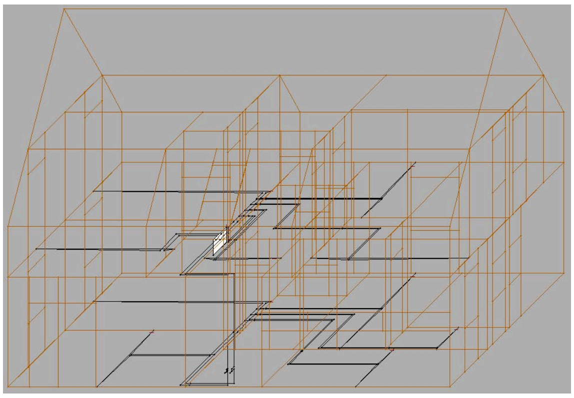


Fig. 5 – Single-family building in TRNSYS-TUD

A detailed description of the model can be found in [17]. The building is set up as follows:

- Heated floor space: 158 m^2
- Heating load according to DIN EN 12831 [18]: 53 W/m^2
- Domestic hot water profile “L” according to EN 13203-4 [19]

Energy system

The energy system contains the following parts (see Fig. 6):

- Underfloor heating system according to DIN EN 1264-3 [20]
- Air-to-water heat pump with cooling function, outdoor installation
- Gas condensing boiler
- Photovoltaic plant
- Thermal storages (heating and cooling)
- Electrical storage

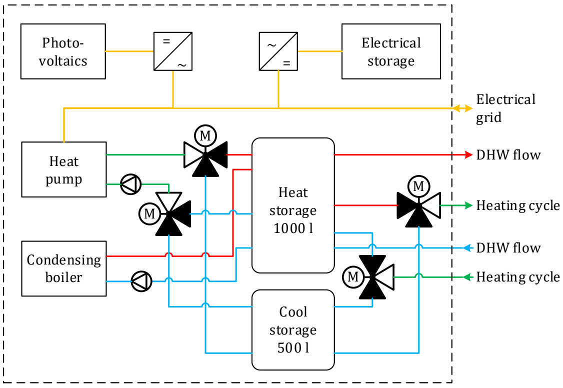
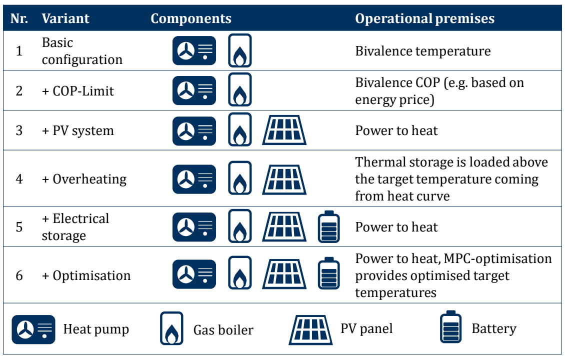


Fig. 6 – Energy system under consideration

Software-in-the-loop (SiL)

The system controller was first tested in a software-only environment. The communication via MQTT thus only took place between simulation and system controller, i.e. both the building and the energy system were simulated. A variant study with year-simulations was carried out in which the system controller, starting from a “basic configuration” with the heat pump and the condensing boiler, was increasingly extended with functions and clients to improve the operation of the energy producers. The variants with the operational premises to switch on/off the heat pump according to Fig. 7 were considered.

Starting from switching-on the heat pump only considering a fixed bivalence temperature (variant 1), the heat pump in variant 2 is switched-on if a predicted COP value exceeds a specified limit value. In variant 3, a PV system is added and PV yield is used for driving the heat pump. To use more of photovoltaic yield, the thermal storage can be overheated additionally in variant 4. With a battery in variant 5, the flexibility on the electrical side can also be used for the system control. Variant 6 includes all options and controls the system with an MPC algorithm.



Nr.	Variant	Components	Operational premises
1	Basic configuration	Heat pump, Gas boiler	Bivalence temperature
2	+ COP-Limit	Heat pump, Gas boiler	Bivalence COP (e.g. based on energy price)
3	+ PV system	Heat pump, Gas boiler, PV panel	Power to heat
4	+ Overheating	Heat pump, Gas boiler, PV panel	Thermal storage is loaded above the target temperature coming from heat curve
5	+ Electrical storage	Heat pump, Gas boiler, PV panel, Battery	Power to heat
6	+ Optimisation	Heat pump, Gas boiler, PV panel, Battery	Power to heat, MPC-optimisation provides optimised target temperatures

Heat pump   Gas boiler   PV panel   Battery

Fig. 7 – Variants executed in the variant study

The objective function of MPC is the reduction of total system operational costs, which are eventually composed of the costs for operating the condensing boiler and the heat pump and the income from the feed-in tariff, see equation (6). The MPC result is used to determine optimised target temperatures for the thermal storages. The flexibility resulting from the system energy demand, generator outputs and storage capacities, the so called “energy trend band”, is used for this purpose. This basic approach has already been successfully tested in further scientific projects with a focus on sector coupling in regional virtual power plants [12], [21]. The whole algorithm is shown in Fig. 8.

$$C_{tot} = \min(\sum_{t=0}^{T} C_{HP,t} + C_{boiler,t} - I_{PV,t}) \qquad (6)$$

Hardware-in-the-loop (HiL)

In a parallel step, the energy system was transferred from the simulation to the real environment, named as “Combined Energy Lab 2.0” [22] shown in Fig. 9 and 10. The Combined Energy Lab 2.0 consists of three main test facilities that are coupled together. Test facility 1 is the indoor climate room used for testing heat transfer and indoor air quality / thermal comfort issues. Test facility 2 is the outdoor climate room with the capability to set the humidity and air

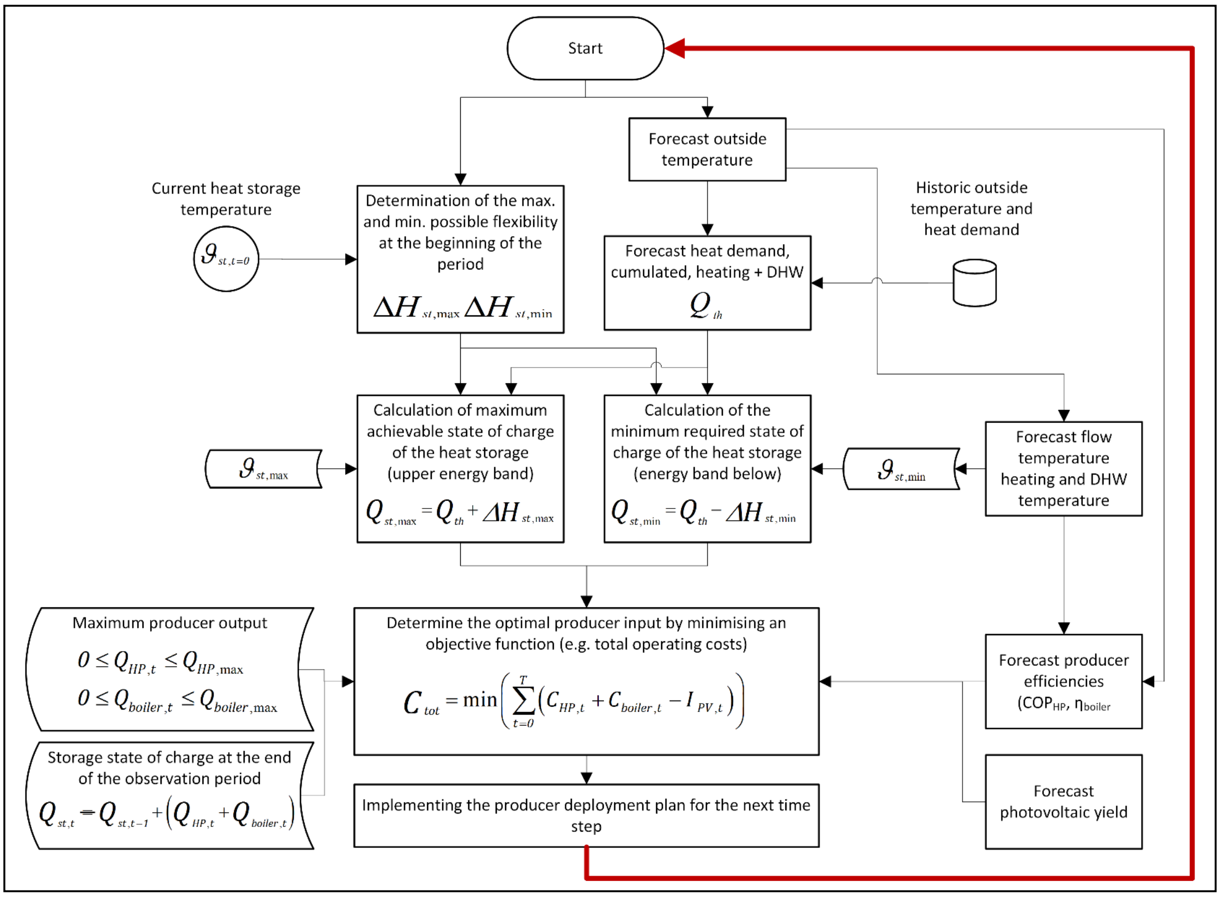


Fig. 8 – Basic MPC algorithm

temperature in a range from $\vartheta_a = \text{-}18\ °C \ldots 35\ °C$, which is used e.g. for testing heat pumps. To ensure the reaction of the building and to be able to perform real-time tests, the so called "energy park" is necessary. The energy park includes heat generators, thermal storage tanks and a hydraulic module for coupling with the building simulation. On the one hand, the required measured values are obtained at the hydraulic module and, on the other hand, the return values from the simulation are set via control valves.

Within the energy park, a low-voltage emulator is also integrated, with which it is possible to vary the characteristics of the electrical distribution network.

The Combined Energy Lab 2.0 offers the possibility to analyse complex energy supply structures. However, since the test time is limited to real time, a type day procedure was developed with which an annual test can reduced to 5 representative type days. Details of the method are documented in [17].

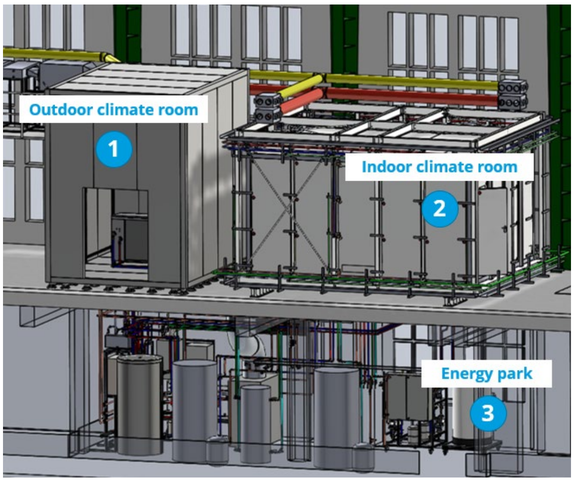


Fig. 9 – Overview about the Combined Energy Lab 2.0

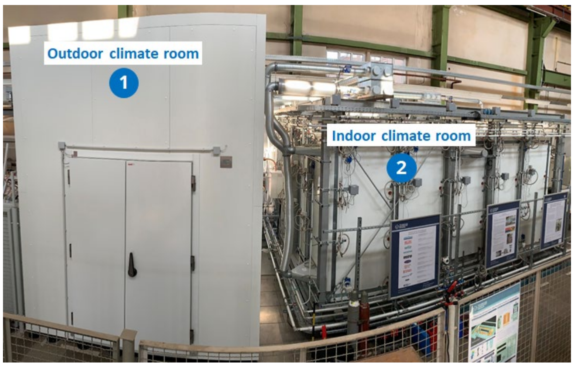


Fig. 10 – Photography of the Combined Energy Lab 2.0

3.2 SiL results

Due to the increasing extensions of the functionalities of the system controller, an increasing needs-based cost reduction can be achieved, as shown in Fig. 11. Regarding e.g. the costs, a reduction of 48 % in the latest expansion stage is possible, depending on the system under consideration. The MPC algorithm can also be used to minimise the CO_2 emissions. However, this was not in the scope of the project.

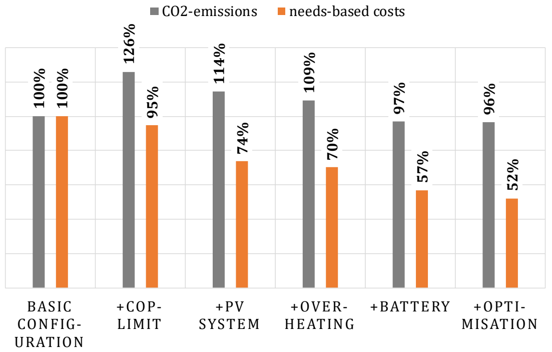


Fig. 11 – SiL results regarding CO2 emissions and needs-based costs

At the same time, it can be seen in Fig. 11 that the MPC control itself provides relatively small cost savings of 5% compared to variant 5 (rule-based algorithms). Here, object-related cost-benefit analysis is required to determine whether the additional expenditure is economical specifically for the forecasts. Furthermore, it can be seen that variants 2-4 lead to higher CO_2 emissions compared to variant 1. This can be explained by the energetically optimised mode of operation, which causes the gas boiler to be switched on more often.

The cost saving of variant 4 compared to variant 5 is caused by the significant increase in the share of self-use of the photovoltaic yields, as the corresponding proportions according to Fig. 12 illustrate. The controlled overheating of the thermal storage tank can also considerably increase the proportion of solar electricity that is used for self-consumption (variant 4 compared to variant 3).

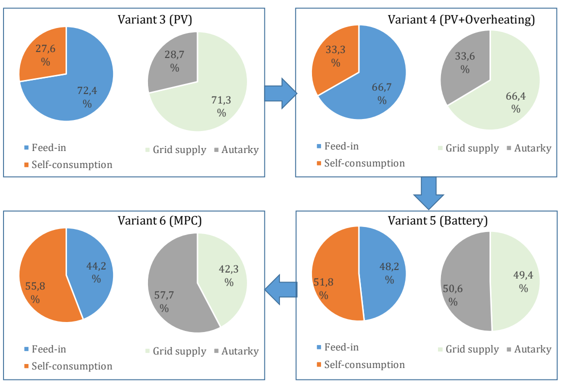


Fig. 12 – SiL results regarding proportions of electrical energy use

3.3 HiL results

The HiL method is particularly useful for repeating tests with identical boundary conditions. Furthermore, there is no longer any dependence on simulation models of the power generation system. Within the project, the reproducibility of representative days can be ensured with a high accuracy. An example is shown in Fig. 13 for a cold representative day, which was conducted three times in total.

Further analyses with regard to the real system behaviour in comparison to the simulation are currently being carried out.

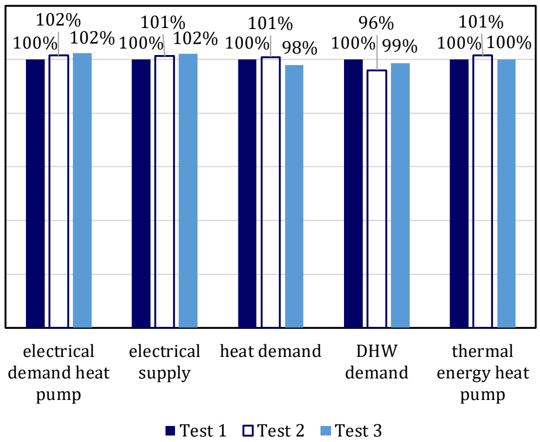


Fig. 13 – HiL reproducibility accuracy of a cold representative day

4. Conclusion

This paper presents the structure, mode of operation and the potential of a system controller in the context of the internet of things. The results are representative but exclusively valid for the system under consideration. Using the highest expansion of the system controller, a needs-based cost reduction of 48 % is possible. However, rule-based algorithms can already reduce costs significantly compared to simple control. Of course, the additional installation costs for the considered additional components must be taken into account. In particular, the MPC-algorithm is able to reduce or expand its influencing factors or change the objective function. Regarding HiL (or field tests), the system controller can be located completely elsewhere than the energy system or the building (simulation), e.g. in cloud-services, and transient Key Performance Indicators (KPI) can be determined.

5. Acknowledgement

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6. Symbols and abbreviations

C_{tot}	Total costs	€
$C_{HP,t}$	Total costs for the heat pump	€
$C_{boiler,t}$	Total costs for the boiler	€
$f_{sky,i}$	clear-sky factor	
$I_{PV,t}$	feed-in income	Wh
m_i	Slope	Wh/°C
Q_{i+1}	Heating energy demand forecast	Wh
$Q_{i,j}$	Past heating energy	Wh
$\bar{Q}_i$	Mean past heating energy	Wh
ϑ_a	Outside temperature	°C
$\vartheta_{a,i+1}$	Outside temperature forecast	°C
$\bar{\vartheta}_{a,i}$	Mean past outside temperature	°C
t_i	Ordinate intercept	Wh
$W_{PV,i}$	PV energy output	Wh
$W_{PV,i+1}$	PV energy output forecast	Wh

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Data access statement

The datasets generated and analysed during the current study are not available because patent protection law votes are currently being carried out but the authors will make every reasonable effort to publish them in near future.