Hardware-in-the-loop integration of PVT models using Internet of Things-enabled communication

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Summary

This paper proposes a Hardware-in-the-Loop (HiL) simulation architecture incorporating Internet of Things (IoT)-enabled communication using Message Queueing Telemetry Transport (MQTT), a lightweight protocol, making distributed messaging possible. The communication procedure between TRNSYS, BCVTB and Matlab as the simulation part and LabVIEW as communication node to the hardware of the real system, is described. Three different HiL test approaches have been compared and the selection of representative days using k-means clustering is depicted, incorporating space heating demand and weather conditions. Results from applying the HiL framework on a parallel solar heat-pump system with emulated covered PVT collectors, show acceptable differences in the collector output temperature and the thermal power output between simulation and hardware. These are found to be caused by time delay in the communication and dynamic limits of the volume flow control in the PVT collector circuit.

Keywords: HiL, PVT, simulation, MQTT, IoT, TRNSYS, MATLAB, LabVIEW

1. Introduction

Hybrid photovoltaic-thermal (PVT) collectors represent a compact solution, converting solar energy in thermal and electrical energy, where installation area is limited but solar supported heating is desired or necessary. PVT provide an alternative heat source for heat pump (HP) systems especially in urban regions with high building density where air source heat pumps come close to their limits regarding legal requirements in relation to noise emissions. Therefore, testing PVT systems in different application scenarios (e.g. as additional energy source in fossil fuel driven heating systems or as heat source for heat pump systems) is important to figure out the potential of reducing fossil fuels consumption or electrical grid demand.

To cope with the fluctuating nature of renewable energy sources and the complexity of modern building energy systems, modeling and simulation studies offer an efficient way for scenario research, like accounting for different locations, weather conditions and building standards. Further they allow for system design and analysis of the systems dynamic behavior in different concepts, as presented in Hadorn (2015) and Frank et al. (2010) or building energy supply systems.

Hardware-in-the-Loop (HiL) approaches offer a high degree of freedom in testing. A HiL simulation combines computer simulation with a separate hardware testbed acting as an embedded system. The HiL approach is cost effective and allows to investigate the performance of a complete system or system components. It is especially useful for rapid control prototyping and validation.

In previous works, Jonas et al. (, 2019) developed a PVT model in the TRNSYS simulation tool (TRNSYS, 2020). In this contribution, the authors have developed a networked HiL framework in the solar laboratory at htw saar that emulates PVT collectors and integrate them into a complete solar heat pump (SHP) building energy system with hydraulic circuit, thermal storage tank and battery storage system. The system concept, which is under consideration in this contribution, is a *solar ground source heat pump* system with connection of the PVT collector to the thermal storage tank in *parallel* to the heat pump (SGSHP-P). Space heating (SH), domestic hot water (DHW) and domestic electric power (DEP) demand profiles have been generated from simulation data of the corresponding system using the TRNSYS model library SHP-SimLib (Jonas, 2023) for a single family household with an annual heat demand of 45 kWh/m² (SFH45) in Strasbourg.

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The HiL architecture designed in this work contains TRNSYS as simulation tool, Building Controls Virtual Test Bed (BCVTB) (Wetter et al., 2008) as middleware for real-time simulation and communication between TRNSYS and MATLAB (MATLAB, 2017) using Berkeley Socket Distribution (BSD) socket connection. MATLAB provides network communication to LabVIEW (Bitter et al., 2018), which acts as software interface to the real system testbed. In addition to acting as a software interface, BCVTB also guarantees real time synchronization of the simulation and the data acquisition and control tools in the testbed.

The paper is structured as follows: following Section 2 explains the system model incorporating the PVT collector in the simulation software TRNSYS as a use case for the HiL simulation platform. In Section 3 identification of representative days of a year for SHP system analysis is described. Section 4 discusses the Hardware-in-the-Loop framework and network communication using Internet-of-Things (IoT) messaging protocol Message Queuing Telemetry Transport (MQTT) in detail and in Section 5 key performance indicators are defined and results are discussed.

2. PVT collector system model

The simulation model has been created in TRNSYS (2020). It is part of the SHP-SimLib from Jonas (2023) and includes the developed TRNSYS Type 835 of a PVT collector (Jonas et al., 2010). The complete model can be subdivided into four sub models (cf. Fig. 1):

- PVT
- Weather
- MATLAB interface
- Output

In the PVT sub model, the collector model TRNSYS Type 832 (Haller et al., 2014) calculates the thermal collector output, where the mean fluid temperature influences the electrical power output, which is calculated in TRNSYS Type 835. Type 31 considers thermal energy losses in the inlet pipe to the collector with ambient temperature as an average of room and outside temperature. A two-point hysteresis controller controls the collector circulation pump with a constant volume flow. As input signals it needs the current temperatures in the DHW and SOLAR zone of the storage tank.

In the weather sub model, weather data for Strasbourg was generated by Meteonorm (2009). Here, long wavelength radiation downwards from sky to the collector plane will be calculated using the fictive sky temperature.

The MATLAB interface is realized by using BCVTB as middleware. Type 6666, provided by the TRNSYS vendor Transsolar, enables TRNSYS to send and receive data to and from MATLAB.

The calculated powers will be integrated over time and the resulting energies will be written to output files.

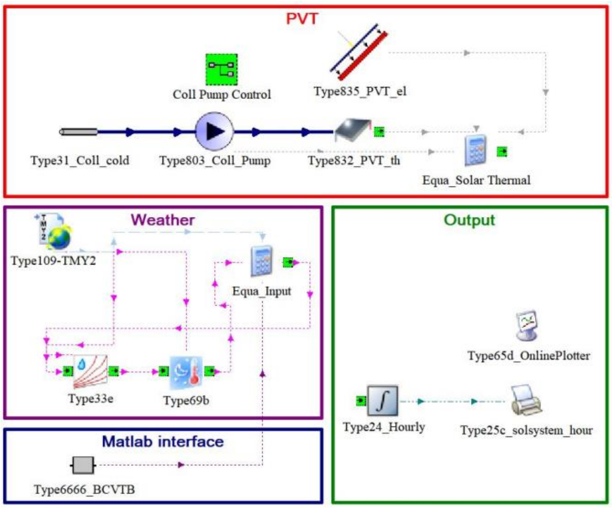


Fig. 1: TRNSYS PVT collector system simulations model

3. Choosing Representative Test Days

Within the last few years, several HiL test methods have been established for testing a SHP system, which will be described in this section. It should be noted that none of the examined methods could be completely adopted. Instead, a standalone test procedure was developed and described briefly. The common approach among the methods is the installation and testing of the system in a laboratory test bench or emulation in real time if some of the components are not installed and, mainly because of economic reasons, the choice of a set of representative days of a year. The selection of these days is still a critical step in the procedure, refer to Menegon et al. (2017). All methods describe a short test cycle and an emulation of boundary conditions. This can be a 6-day test cycle or, less often, a 12-day test cycle.
Among the existing HiL test methods, following three methods have been taken under consideration:

- *Concise Cycle Test* (CCT)
  CCT is a dynamic test method developed at the Institute of Solar Technology, Rapperswil, Switzerland (SPF) for testing systems for heat supply. The method describes a six-day test cycle in which an entire building is supplied with heat. The results should provide information about the performance data of an entire year by extrapolation (Haberl and Haller, 2018).
- *Prescribed Load Performance Extrapolation* (PLPE)
  PLPE is a test procedure that can be applied to several locations. The locations used so far are Bolzano (Italy), Zurich (Switzerland), Gdansk (Poland) and Rome (Italy). For all locations, weather data from Meteonorm have been used, while demand for SH and DHW vary depending on the locations. As with CCT, a room temperature of 20 °C is specified and a two-storey single-family house with an area of 180 m² is simulated (Menegon et al., 2017).
- *New Materials and Control for a next generation of compact combined Solar and heat pump systems with boosted energetic and exergetic performance* (MacSheep)
  As part of the EU research project MacSheep (Haberl et al., 2015), a method was developed, with the intention to harmonize the test procedure of SERC and SP (both Sweden), INES (France) and the SPF (Switzerland). In the test bench, energy storage, auxiliary heater, all devices for SH and DHW preparation, all devices related to the solar circuit, pumps and pipe connections, controllers, and temperature sensors are considered for evaluation.
  The simulation is based on EN ISO 13790-2008 considering a single family house based on the International Energy Agency (IEA) Solar Heating and Cooling Programme (SHC) Task 44 / Heat Pump Programme (HPP) Annex 38 (IEA SHC, 2013) with a heating energy requirement of 45 kWh/m²a (SFH45) for a test period of 6 and 12 days, not taking into account an electrical load profile. As reference location, Zurich has been chosen and weather data has been simulated with TRNSYS using weather dataset from Meteonorm. Tests will be done with criteria of CCT (e.g., preconditioning of the storage tank).

The test methods differ in the following points (Menegon et al., 2018):

- Choice of test sequence
- Definition of load profiles
- Emulation of the components which are not installed in the test bench
- Extrapolation of seasonal performance factors on other climates
- Application of climate data and load profiles

While MacSheep only slightly differs from the CCT method, PLPE is a completely new approach when it comes to the heat distribution and choice of weather data for the test.
Unfortunately, neither MacSheep nor PLPE describe a DEP consumption. CCT is the only available recent method, which presents a DEP load. The total DEP demand is of a high interest in a household with a SHP system, especially in the context of a Smart Grid.

CCT in the latest version (Haberl and Haller, 2018) uses an optimized ambient temperature and irradiation in the test sequence with the aim to match the annual demand after extrapolation. However, as of the latest versions of those procedures, the weather file is modeled according to the space heating demand of the simulated and emulated building, which is not the case in our approach.

In this approach the SH demand profile generated in TRNSYS and applying the k-means clustering algorithm in MATLAB, six representative days have been determined. These are selected in such a way that they are nearly corresponding to the nominal SH demand value of 45 kWh/m²a (SFH45). From the identified clusters, days 4 and 2 are chosen in such a way that the former has a high ambient temperature at a high irradiation and the latter has a high ambient temperature at low irradiation. For the six representative days determined, this results in a total SH energy demand of 111.64 kWh, which corresponds to an annual energy demand of 6791.4 kWh after multiplication with 365/6, respectively 48.5 kWh/m²a for a SFH45 reference building with a heated living area of 140 m².

When selecting the days, the global horizontal irradiation and the ambient temperature were determined in such a way, that these days reflect the different weather conditions of the whole year.

The days of the matching sequence are 41, 101, 111, 272, 321, 331 and are listed in Table 1 with corresponding SH demand and weather conditions.

Tab. 1: Identified representative Days of the year, corresponding date and number of days in the year

No.	**Number of Representative Day of the Year**	**Corresponding Date of the Year**	**Daily Space Heating Energy [kWh]**	**Weather Characteristic of the Day** $^{1),2)}$
1	41	10.02.	39.93	GHI: high ;AT: low
2	101	11.04.	0	GHI: variable; AT: high
3	111	21.04.	2.3	GHI: low; AT: low
4	272	29.09.	0	GHI: high; AT: high
5	321	17.11.	39.15	GHI: low; AT: low
6	331	27.11.	30.26	GHI: high; AT: low
Σ			111.64	

1) GHI: Global Horizontal Irradiance (high: > 600 W/m², low: < 600 W/m²; variable: > 600 W/m²)
2) AT: Air Temperature (low: (< 15 °C, high: > 15 °C)

4. Hardware-in-the-loop framework

In this section, the development of the networked Hardware-in-the-loop framework will be described in detail. The HiL architecture incorporates TRNSYS as simulation tool, BCVTB as middleware for real-time synchronization and communication between MATLAB and LabVIEW that acts as software interface to the real system testbed. Messaging between MATLAB (simulation) and LabVIEW (real system) is established using MQTT. The developed HiL test bench allows to perform component specific test procedures on the one hand as well as dynamic tests of the complete SHP system, where different thermal and electrical sources and loads can be emulated.

Thermal and electrical demand profiles (SH, DHW, DEP) have been generated through simulation of the SGSHP-P system in TRNSYS using the defined boundary conditions of IEA SHC Task 44 / Annex 38. Here Strasbourg as location with corresponding weather conditions and a single-family household (SFH) with nominal annual space heating demand of 45 kWh/m² (SFH45) was applied. The results are converted to CSV file format and directly loaded by LabVIEW and applied to the real system.

Whole the load demand profiles are independent from the current state of the reals system, the PVT simulation model depends on the current states in the test bench, due to the input volume flow rate and input temperature from the storage tank in the real system to the PVT collector in the simulation model.

The HiL architecture uses MQTT communication protocol, which is a lightweight, open and simple messaging protocol, ideally applicable for distributed communication, transmitting data between multiple, resource-constrained devices having low bandwidth and low power requirements. Therefore, an appropriate application is transmission of sensor data in poor quality networks. MQTT runs in the application layer, over the TCP/IP layers that provide a lossless and bidirectional transmission of any type of data. It is a client-server messaging protocol that encapsulates the one-to-many message distribution of the publish-subscribe model into TCP/IP, making it suitable for use in Machine-to-Machine (M2M) communication and the Internet-of-Things (IoT) architecture, where lots of devices and sensors are connected across the Internet.

The one-to-many architecture is highly suited to control, where a single message to a single channel, called topic, could be used to control many thousands of devices at once.

The publish-subscribe model involves multiple clients with each other, without having any direct connection established between them. All clients communicate with other clients via a central server, called broker. It routes the messages to the appropriate subscribing clients.

As mentioned before, MQTT operates on a channel-wise communication, meaning that it operates on a hierarchical ‘topic’ structure so that systems can be logically grouped based on application requirements. For example, devices can be grouped into areas in relation to the connected infrastructure, as electrical or thermal subsystem in a residential energy system. Topic subscriptions can include wildcards so that a variety of advanced data filtering can be utilized. For example, a device can subscribe its specific control topic and publish on a specific sensor topic, while the controller subscribes all sensor topics easily through wildcard in the sensor layer in a hierarchical structure. Due to the use of TCP, MQTT connections can be made inherently secure using TLS/SSL, while additional security can easily be added to MQTT systems using authorization servers for publish or subscribe requests.

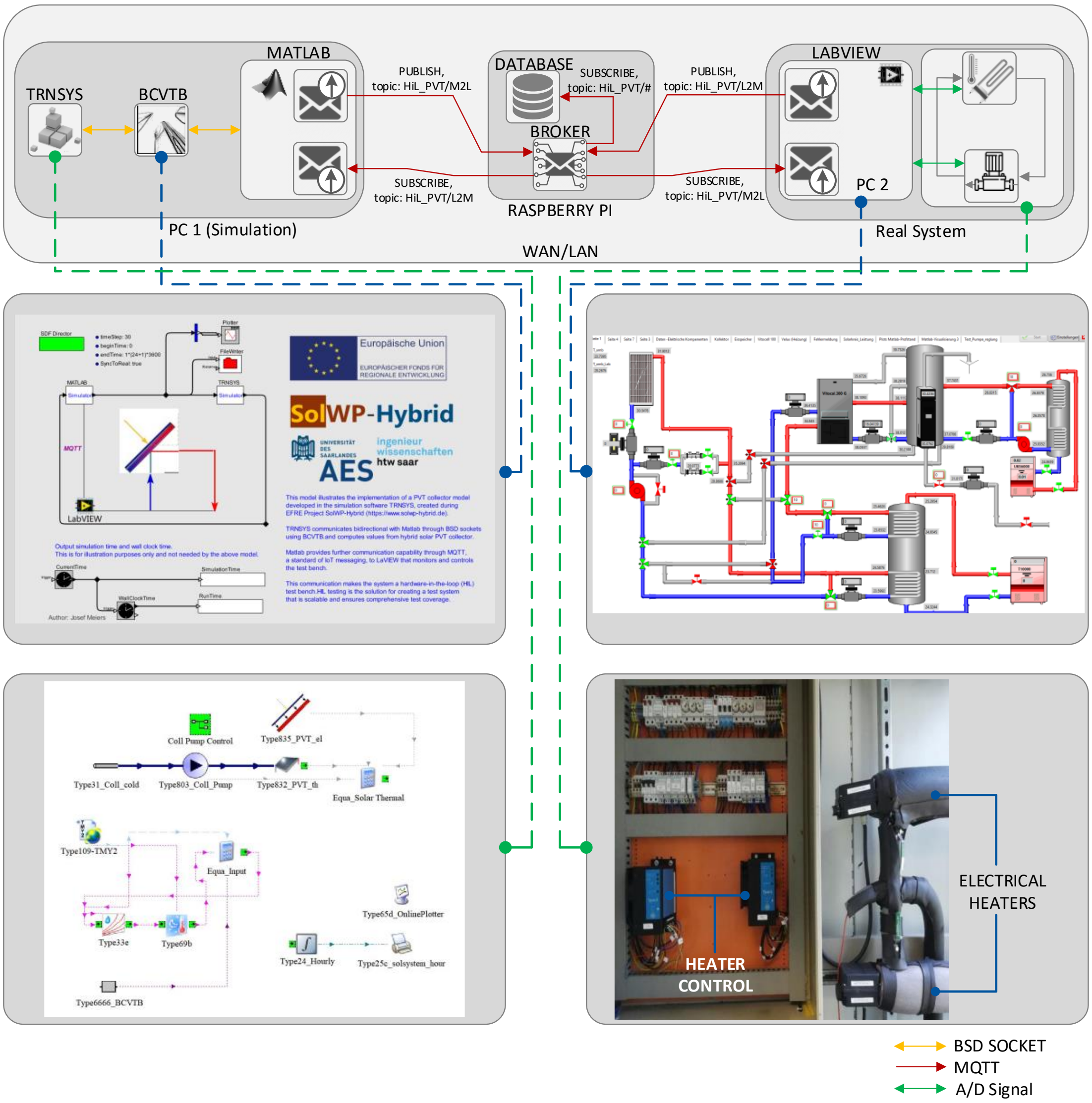
MQTT has been ratified as an OASIS (Organization for the Advancement of Structured Information Standards) standard in October 2014 (OASIS Standard, 2014) and 2016 as an ISO/IEC 20922 standard (ISO/IEC 20922:2016, 2016), which guarantees consistency across implementations. It has built-in Quality of Service (QoS) mechanisms, which can guarantee message delivery from client to broker, or vice-versa: Depending on the QoS level, communication data increases from QoS 0 to QoS 2

- QoS 0: a message is delivered at most once, without an acknowledgement.
- QoS 1: a message is delivered at least once but duplicates can occur.
- QoS 2: a message is delivered exactly once.

QoS is important because it enables to manage the network quality by controlling the protocol overhead when connection problems occur or bandwidth is low. In our contribution, where the amount of transmitted data is comparatively low, we use QoS 2 to ensure message delivery only once. Mosquitto (Light, 2017) is used as MQTT broker (server) and running on a raspberry pi embedded system.

The HiL architecture we implemented is based on a decentralized communication infrastructure and has some advantages compared to a centralized implementation:

- HiL simulation can run on different computers in the local area network (LAN). As in our work, we run the simulation with MATLAB as one client on one computer (PC1) and LabVIEW as second client and interface to the test bench on another computer (PC2). Therefore, it is also possible to run simulation via remote connection over longer distance from the test bench in a wide area network (WAN).
- In general, any simulation software or algorithm can be used that can handle received data and transmit the data in the appropriate format.
- MQTT protocol and its topics allow a hierarchical message structure depending on the system design, e.g. *\thermal system\heat pump\power consumption* or *\electrical system\PVT\power production.* This allows an efficient message handling, where devices can subscribe and publish only their specific data. For example, where MATLAB receives only data from LabVIEW of topic *\HiL_PVT\L2M* and LabVIEW from MATLAB of topic *\HiL_PVT\M2L*, it is useful, that an additional database client receives data from all topics using a wildcard *\HiL_PVT\#.*
- The extension of the system (sensors and actuators) in future works can be easily realized by installing MQTT enabled devices as provided now by leading manufacturers of instrumentation products.
- The *Last Will and Testament* feature of MQTT provides a way for clients to respond to ungraceful disconnects in an appropriate way. If a client has been disconnected in an improper way the broker sends a predefined message to all the clients. This could help to set the system in a safe state.



- timeStep: 30
- beginTime: 0
- endTime: 1*(24+1)*3600
- SyncToReal: true

Output simulation time and wall clock time.
This is for illustration purposes only and not needed by the above model.

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This model illustrates the implementation of a PVT collector model developed in the simulation software TRNSYS, created during EFRE Project SolWP-Hybrid (https://www.solwp-hybrid.de).

TRNSYS communicates bidirectional with Matlab through BSD sockets using BCVTB and computes values from hybrid solar PVT collector.

Matlab provides further communication capability through MQTT, a standard of IoT messaging, to LaVIEW that monitors and controls the test bench.

This communication makes the system a hardware-in-the-loop (HIL) test bench.HIL testing is the solution for creating a test system that is scalable and ensures comprehensive test coverage.

Fig. 2: Hardware-in-the-loop framework (top layer: main architecture of the software tools and communication, middle left: BCVTB model, middle right: LabVIEW visualization of the solar heat pump testbench, bottom left: TRNSYS model of PVT collector, bottom right: electrical heater for thermal power output emulation of PVT collector)

In Figure 2, the architecture of the HiL simulation is visualized, showing the software, networked interconnection with MQTT topics, BCVTB model, LabVIEW visualization of the SHP system, TRNSYS model of the PVT collector subsystem, and the heating system, which emulates the thermal power output of the simulated PVT collector.

In the HiL framework, MATLAB acts as a master to control the simulation entry point. Users start both software endpoints, MATLAB and LabVIEW. After starting MATLAB, it waits, until it receives the first message from LabVIEW, where the considered date and time is given. MATLAB then writes the TRNSYS deck-file with new start date and starts the BCVTB model via command line. BCVTB initializes the TRNSYS model and corresponding MATLAB script in a separate process.

The simulation time step in TRNSYS is 20 seconds (dt_{RT}) and the cycle time step in LabVIEW is 10 seconds (dt_{LV}), where all sensor values will be measured and send via MQTT and actuator values will be received and set. BCVTB stops execution of the simulation after each simulation time step until a real-time timer has fired. Therefore, LabVIEW will only transfer and receive at each second time step of the LabVIEW program loop messages from and to MATLAB. In case, LabVIEW will not receive any data it will do no change in the control (cf. Figure 3).

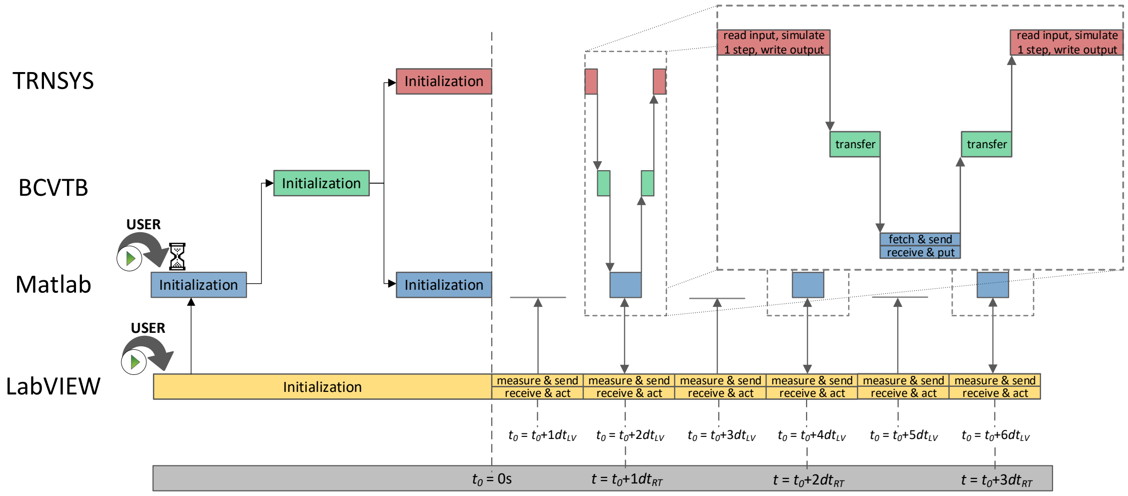

Fig. 3: Visualization of software timing schedule during Hardware-in-the-Loop simulation

In the TRNSYS model of the PVT collector system, outlet fluid temperature ($T_{PVT,out,sim}$), thermal ($\dot{Q}_{PVT,sim}$) and electrical ($W_{el,PVT,sim}$) power outputs are calculated under the given weather conditions also calculated in the simulation. Beside this, control of the PVT collector circulation pump has been implemented in the simulation model. The control signal ($s_{PVT,sim}$), whether solar circulation pump is switched on or off is also an output signal. On the other side, LabVIEW provides four measured values as input signals to the simulation. Temperature of the inlet fluid flow ($T_{PVT,in,testbench}$) and the volume flow rate ($\dot{V}_{PVT,testbench}$) have to be given to the PVT collector model, while storage tank temperature of the DHW area ($T_{ST,DHW,testbench}$) and SOLAR area ($T_{ST,SOLAR,testbench}$) need to be used for decision making of the controller of the PVT collector circulation pump. Input and Output signals are summarized in Table 2.

Tab. 2: Output and input values from and to MATLAB and LabVIEW (M2L: MATLAB to LabVIEW, L2M: LabVIEW to MATLAB)

Output (M2L)		**Input (L2M)**	
PVT collector thermal power	$\dot{Q}_{PVT,sim}$	PVT collector fluid input temperature	$T_{PVT,in,testbench}$
PVT collector electrical power	$W_{el,PVT,sim}$	PVT collector volume flow rate	$\dot{V}_{PVT,testbench}$
PVT collector fluid output temperature	$T_{PVT,out,sim}$	Storage tank DHW temperature	$T_{ST,DHW,testbench}$
PVT collector circulation pump state (ON/OFF)	$s_{PVT,sim}$	Storage tank SOLAR temperature	$T_{ST,SOLAR,testbench}$

5. Results

In this section, we will discuss the quality of the HiL simulation (cf. Section 4) and the results of simulation for the six representative days (cf. Section 3) by introducing two definitions of the seasonal performance factor (SPF) as key performance indicators depending on the system energy boundaries. The SPF quantifies the final energy efficiency of the defined system and is generally defined as the overall useful energy output to the overall driving final energy input over a period of one year.

Here, we consider the time period of the six representative days for its calculation.
SPF with focus on the heat pump (SPF_{HP}) only considers the electrical power consumption of the HP system, considering HP compressor, control system and pumps of internal circulation, heat source and heat sink side (primary and secondary circuit) from grid, PVT collector or battery storage system. Thermal energy production of the HP is measured directly at the output pipes of the HP (cf. equation 1).

Whereas SPF with focus on the solar heat pump systems (SPF_{SHP+}) additionally recognizes the electrical power demand of the SH, DHW and PVT collector circulation pumps (cf. equation 2). While in SPF_{HP} thermal output power behind the HP, at its outlet pipes, is used, in SPF_{SHP+} thermal power extraction behind the storage tank is taken into consideration.

Figure 4 visualizes the energy flows and the energy boundaries for the two SPF definitions.

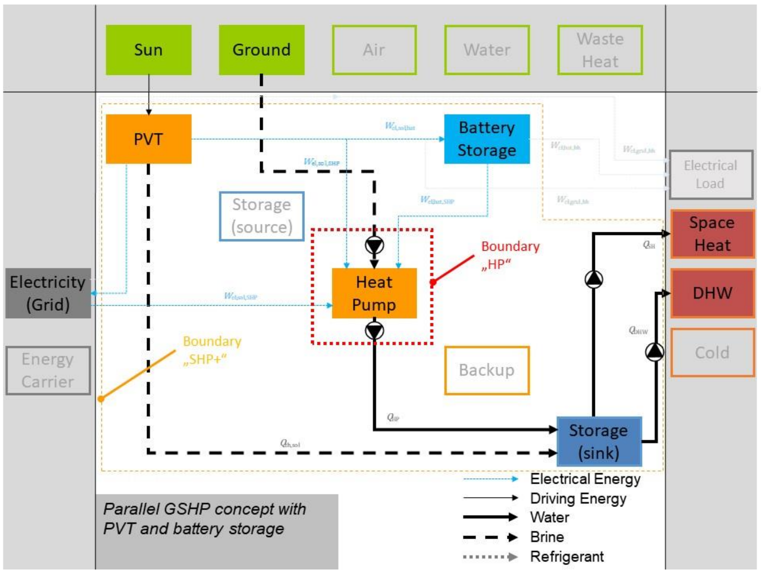

Fig. 4: Visualization of energy flows and boundaries for SPF definitions in the considered solar heat pump system

$$SPF_{HP} = \frac{Q_{HP,SH} + Q_{HP,DHW}}{W_{el,HP}} \qquad \text{(eq. 1)}$$

where:

$Q_{HP,SH}$: thermal energy production of HP for SH [kWh]
$Q_{HP,DHW}$: thermal energy production of HP for DHW preparation [kWh]
$W_{el,HP}$: electrical energy demand of the HP system [kWh]

$$SPF_{SHP+} = \frac{Q_{ST,SH} + Q_{ST,DHW}}{W_{el,HP} + W_{el,DHW} + W_{el,SH} + W_{el,PVT}} \qquad \text{(eq. 2)}$$

where:

$Q_{ST,SH}$: thermal energy tapping from ST for SH [kWh]
$Q_{ST,DHW}$: thermal energy tapping from ST for DHW preparation [kWh]
$W_{el,DHW}$: electrical energy demand of DHW circulation pump [kWh]
$W_{el,SH}$: electrical energy demand of SH circulation pump [kWh]
$W_{el,PVT}$: electrical energy demand of the PVT collector circulation pump [kWh]

Beside the seasonal performance factor, an equivalent definition of the daily performance is introduced with Daily Performance Factor (DPF). Equations 1 and 2 remain the same, only the time period is reduced to one day.

In Figure 5, DPF for each of the six representative days and the resulting SPF for the overall time are shown. Daily performance factors of the complete solar heat pump system (DPF_{SHP+}) range between 1.8 and 4.0, whereas values of DPF_{HP} are in the range of 1.6 to 3.7.

Except day 101, the values of DPF_{SHP+} are better than DPF_{HP}. For days 41, 272 and 331 this is reasonable to a higher usage of solar thermal energy.

Although solar thermal energy is high on day 101, DPF_{HP} is higher than DPF_{SHP+}. This can be explained due to the behavior of the HP controller. On this day, the HP is switched on in the morning to heat up the SH and DHW zone of the storage tank ($Q_{HP,SH}$, $Q_{HP,SH}$ high) although there is no space heating demand ($Q_{ST,SH}$ low). Additionally, the PVT collector will also charge the storage tank. The amount of heat produced by the heat pump on this day is higher than the heat demand, even without solar thermal energy entry.

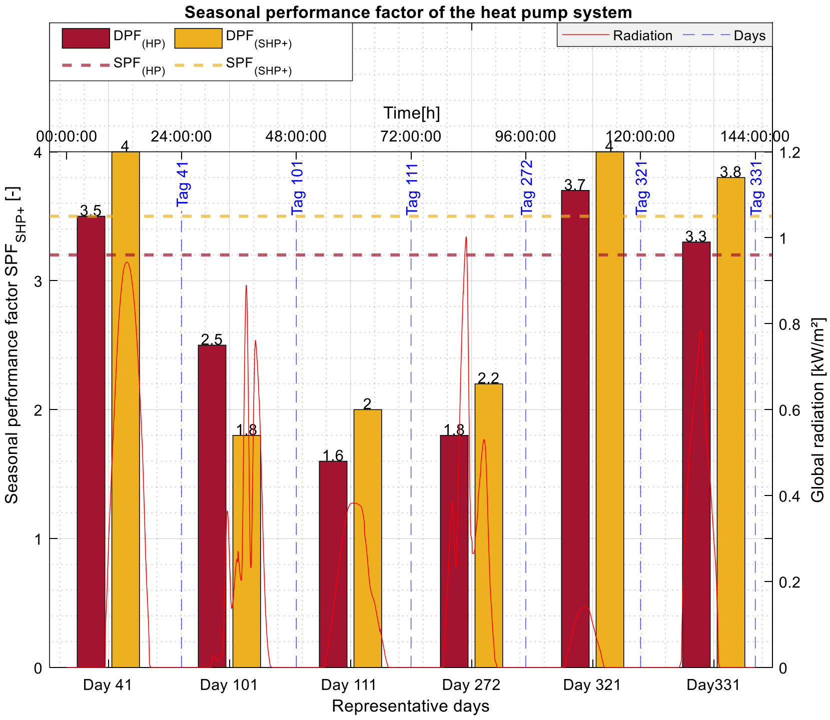

Fig. 5: Daily and seasonal performance factor for representative days and for the entire period in comparison of HP system and complete SHP system

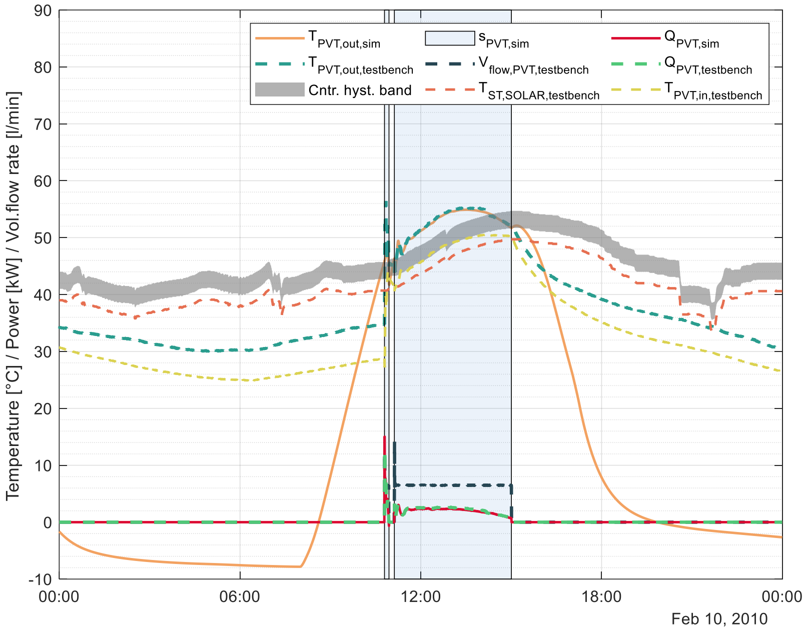

Fig 6:Comparison of simulation and measured values

From Figure 6 it can be seen that the simulated ($T_{PVT,out,sim}$) and measured values of the PVT collector output temperature ($T_{PVT,out,testbench}$) show good accordance in times where the PVT collector circulating pump is switched on ($s_{PVT,sim}$). It can also be seen clearly that there are overshoots in the PVT collector volume flow rate, when the circulating pump is switched on. This leads to oscillating behavior in the measured PVT collector output temperature. At the current state, this is an unavoidable behavior, since the installed volume flow valve is quite slow (it takes about 60 seconds for fully opening) and the implemented PID controller for the volume flow does not recognize the time delay in the simulation framework communication.

It has been observed that this time delay is three simulation time steps and leads to an oscillating behavior. This can be improved by decreasing the HiL simulation time step but is limited due to installed measuring equipment.

Since the electronic power source is very fast to emulate the simulated electric PVT collector power output, deviations can be neglected compared to the thermal system.

Table 3 shows root mean square error (RMSE) (cf. equation 3) for PVT collector output temperature and the thermal power output for each of the six representative days.

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(x - x_{ref}\right)^2} \qquad \text{(eq. 3)}$$

The error is only calculated in time steps, where the circulating pump is switched on. In day 3 and 5 there is no thermal power output, since the calculated output temperature of the PVT collector is not high enough.

Root mean square error of the PVT collector output temperature ($RMSE_T$) ranges from 1.01 to 2.12 K, error of thermal output power ($RMSE_{dQ}$) from 0.62 to 0.82 kW and thermal energy output ($RMSE_Q$) from 0.05 to 0.58 kWh (relative values from 0.8 to 7.3 %). These values derive from the continuous time delay in the communication and from the oscillating behavior of the controller.

As an additional quality criterion, comparing of energies for domestic hot water and space heating preparation and household electricity demand over the entire test sequence show relative deviations of about 1.2-2.8 % and are therefore considered to be small. Concluding from that, the HiL emulation shows satisfactory results, improvements are expected with an improved control of the volume flow rate in the PVT collector emulation loop.

Tab. 3: Root Mean Square Error of PVT collector output temperature, thermal power and thermal energy between simulation and testbench

Day No.	$RMSE_T$ [K]	$RMSE_{dQ}$ [kW]	$RMSE_Q$ [kWh]([%])
1	1.01	0.65	0.58 (7)
2	1.17	0.62	0.48 (7.3)
3	-	-	-
4	2.12	0.82	0.05 (0.8)
5	-	-	-
6	1.55	0.68	0.06 (1.5)

6. Conclusion

The proposed HiL framework is based on a decentralized communication infrastructure, which offers advantages compared to a centralized implementation such as remote simulation. The used MQTT protocol can be secured and the underlying communication protocol TCP is robust. As there is no integrated software tool that fulfills our requirements on modeling and control, we have proposed a new framework that connects the following software tools: MATLAB, TRNSYS, LabVIEW and BCVTB.

We selected six representative days, where the global horizontal irradiation and the ambient temperature were determined in such a way, that these days reflect the different weather conditions of the whole year. This method differs from described test procedures.

In conclusion the comparison of simulated and measured output temperature and thermal energy of the PVT collector in the use case shows that the error can be considered as acceptable small.

7. Acknowledgements

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