Test specifications and experiment plans

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Background Information

This document explains the test specifications, the appliance emulation with NEST facilities and four guiding experiment plans. These test case forms are customized based on the work from Heussen et al. [1] and used to systematically verify the designed functions. Parts of this report will be published in a scientific publication(s).
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Glossary

COP coefficient of performance

DSO distribution system operator

DHW domestic hot water

EV electric vehicle

GB grid-block

HP heat pump

ICT information and communications technology

LSTM long short-term memory

MPC model predictive control

PV photovoltaics

RES renewable energy sources

RMSE root-mean-square error

SH space heating

SOC state-of-charge

TES thermal energy storage

1 Test specifications

Title:	A context-aware residential building energy management system.
Narrative:	Growing RES penetration in the distribution system could lead to reverse power flow as observed in Chapter 10.2. This phenomenon increases voltage violations and affects electricity quality. A traditional solution is to reinforce the network, which is prohibitively expensive. Emerging intelligent building energy management presents a cost-efficient alternative. By utilizing building flexibility, we could address the local issue locally without large-scale grid reinforcement. While building energy management system optimizes its energy usage according to residents' objectives, it is desired that the energy management system quantifies the flexibility and periodically self-reports it to the DSO, which can operate the system flexibly and in a cost-efficient manner. Hence, the test has two main focuses: 1) predictive energy management of the controllable loads in the building; 2) and self-reported flexibility metrics. The test requires the building to be fully digitalized with sufficient control and communication interfaces. More specifically, the goals of the test are twofold: 1) validate the controller design in Chapter **??**; 2) and demonstrate that the controller can extract and communicate the flexibility envelope defined in Chapter **??**.
Domain under investigation:	The overall implementation concerns both the electrical power and the ICT domain with four relevant entities as illustrated in Figure 1: 1) a physical low-voltage distribution network; 2) a distribution system operator; 3) electrical appliances in buildings; 4) and a building energy management system. Real-time user configurations are not considered in the test. Their preferences are incorporated as fixed parameters.
Functions under test:	The functions under test include sub-functions and their integration. More specifically, the sub-functions include: 1) prediction of DHW tank temperature; 2) prediction of SH temperature; 3) prediction of PV production; 4) prediction of battery SOC; and 5) flexibility envelope calculation. All the sub-functions are eventually integrated with a final assessment according to the criteria specified below.
Purpose of investigation:	To validate and evaluate the proposed control algorithm before rolling out in real residential buildings, and evaluate the impacts of the developed controller.

Test criteria:	1) controller stability; 2) reasonable satisfaction of users' comfort and preferences; 3) energy usage is scheduled according to customized objectives; 4) and self-reported flexibility metrics during test runs.
Target metrics:	1) accumulated room temperature deviations below the lower comfort limit; 2) water tank average temperature deviations below the lower comfort limit; 3) total energy usage; 4) total energy cost; 5) and total equivalent emission.
Uncontrollable:	1) water draw; 2) door/window opening; 3) EV arrival/departure times and SOC at arrival; 4) uncontrolled loads as shown in **??**; 5) weather forecast errors; and 6) electricity carbon footprint, electricity cost and feed-in-tariff.
Controllable:	1) electric power of HPs; 2) charge/discharge of electric battery; 3) PV active power curtailment; 4) and EV charge/discharge when connected to the charger.
Test system	The full system configuration is illustrated in Figure 5.
Input and output	See Table 2 and Table 3.
Data storage	A server at Empa.
Temporal resolution	1) the optimization is executed every 15 minutes; 2) the external communication frequency is listed in Table 2 and Table 3; 3) and the temporal resolutions of measurements are summarized in Table 14.
Source of uncertainty	1) weather forecast errors; 2) modelling errors; 3) metering precision; 4) EV arrival and departure time; 5) fixed load forecast error; 6) and carbon intensity forecast error.
Suspension criteria	1) a stable controller with flexibility envelope communication; 2) user comforts and preferences are sufficiently respected; 3) and evidences of energy scheduling according to customized objectives.

Table 2: List of data inputs, sources and update frequency.

Input	Source	Update frequency
Irradiance forecast	FTP server/Meteoswiss	every 12 hours
Temperature forecast	FTP server/Meteoswiss	every 12 hours
CO_2 intensity forecast	aliunid's server	every 24 hours
Dispatch signals	GB 2	on request

2 Emulators

This chapter describes how the equipment at NEST is adapted and configured to emulate the HPs for SH and DHW, battery and PV in typical Swiss residential buildings. During the project, an EV that is capable of bidirectional charging is not available. A computer script is created to virtually emulate an

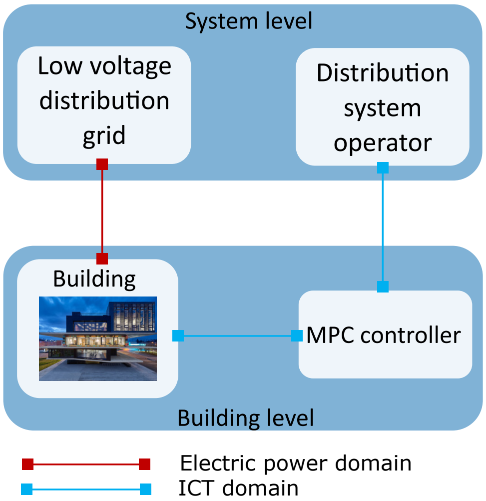

Figure 1: Domains under investigation and relevant entities including a low-voltage distribution network, a DSO, the NEST infrastructure and the developed controller.

Table 3: List of outputs, destination and update frequency.

Output	Destination	Update frequency
Flexibility envelope	GB 2	every 15 minutes
Set points	devices listed in Table 14	$\leq$ 5 seconds
Watchdog signals	devices listed in Table 14	$\leq$ 5 seconds

EV to include its energy consumption and flexibility, as it represents a crucial source of flexibility in the future. Emulators are created considering realistic SH demand and real water draw for DHW demand. Since the devices are physically distributed around NEST, the emulated net power exchange with the grid is obtained by summing up all the timestamped measurements of the appliances.

2.1 Heat pump emulators

The energy demands for SH and DHW are emulated with the UMAR unit. A detailed description of the facilities can be found in [2]. Since there is no dedicated HP for SH at UMAR, the electrical power consumption has to be emulated by discounting the thermal power measurement by its coefficient of performance (COP). In addition, valves for the thermal power inputs are controlled with dynamic duty-cycles to emulate an HP with a variable compressor speed. As for the HP for DHW, the same emulation strategy applies, and it is assumed to have discrete power input with ON/OFF control.

2.2 Battery emulator

Lithium NMC battery at NEST has a capacity of 96 kWh, which is much larger than one would find in a residential building. Hence, we impose artificial minimum and maximum power and energy capacity limits, as summarized below. Note that the battery needs to be initialized to be within the range stated in Table 4 prior to starting the experiments.

Table 4: Specification of battery emulator.

	Max SOC [%]	Min SOC [%]	Power [kW]	Energy capacity [kWh]
Original	57	39.5	[-5, 5]	96
Emulated	100	20	[-5, 5]	17.5

2.3 EV emulator (virtual)

The virtual EV and charger are emulated with the specification listed in Table 5. Both the EV and the charger are emulated to be capable of bi-directional charging. In addition, the EV charger is assumed to inform the controller about the EV's current SOC. EV departure time can either be predefined by the end-users or inferred from historical data. Arrival time is assumed similarly but can also be estimated by the on-board navigation system.

Table 5: Specification of electric vehicle emulator.

	Max SOC [%]	Min SOC [%]	Power [kW]	Energy capacity [kWh]
Emulated	100	20	[-7, 7]	50

3 Experiment plans

Four experiments, namely exp1 to exp4, are designed with an increasing level of complexity. While exp1 to exp3 verify sub-functions, exp4 is designed to integrate all the sub-functions and evaluate the overall performance of an emission-aware building energy management system. The rationale behind such a design process is to eliminate the risk of errors in sub-functions propagating to the final product. It is non-trivial to diagnose issues of sub-functions when they are integrated.

3.1 Experiment plan: exp1

The exp1 is designed to have a sanity check on the controller design, the communication and the actuation interfaces, and the stability of the minimal energy management system, which provides insights for the long-term experiments later on. The objective of this minimal energy management system is given in Eq. (1a) and the experiment plan is detailed in Table 6.

$$\underset{\{u_t|\forall t \in \mathbb{H}\}}{\text{minimize}} \quad \sum_{t\in\mathbb{H}} (r_t^{\text{b2g}} P_t^{\text{b2g}} + c_t^{\text{g2b}} P_t^{\text{g2b}}) \Delta\tau_t + w_4 (\epsilon^{\text{ebat}})^2 \tag{1a}$$

where $\{u_t|\forall t \in \mathbb{H}\} := \{P_t^{\text{ebat, ch}}, P_t^{\text{ebat, ds}}, P_t^{\text{pv}}|\forall t \in \mathbb{H}\}$ is the set of control variables, $r^{\text{b2g}} \in \mathbb{R}_+$ and $c^{\text{g2b}} \in \mathbb{R}_+$ are the feed-in-tariff and the grid tariff respectively. The full optimal control problem includes a subset of the constraints formulated in Eq. (**??**). For the sake of conciseness, we do not detail them again.

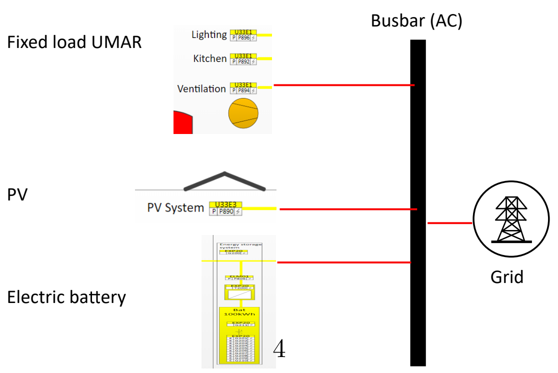

Figure 2: Single-line diagram of the electrical system configuration in exp1.

Table 6: Experiment plan for exp1.

Title	Exp1: a minimal cost-aware energy management system.
Research infrastructure	1) NEST backbone: electrical grid; 2) electrical devices listed in Table 7; 3) NEST REST API and OPC-UA.
Experiment realization	See Figure 2.
Experiment setup	See Table 7.
Experiment objective	The optimization objective is formulated in Eq. (1).
Precision of equipment	See Table 14.
Suspension criteria	Stable run of controller.

Table 7: List of devices included in exp1.

Name	Location	Number of Units
PV	NEST (dfab roof)	1
Battery	NEST	1
Fixed load	NEST (UMAR)	1

3.2 Experiment plan: exp2

This experiment is motivated by the need to validate the modeling accuracy of SH. The strategy is to create an experiment that incentivizes the temperature to approach the predefined temperature limits. If the identified model sufficiently captures the dynamics, the controller is expected to achieve the designed objective while satisfying predefined constraints. We evaluate SH in a standalone experiment because it is known to contribute to a big part of the residential building consumption with dynamics that are challenging to capture entirely. The experiment objective formulated in Eq. (2) leads to both reduced energy consumption and peak power. The experiment plan is detailed in Table 8.

$$\underset{\{u_t|\forall t \in \mathbb{H}\}}{\text{minimize}} \quad \sum_{t\in\mathbb{H}} (P_t^{\text{sh}})^2 \Delta\tau_t + w_5(L_\delta(\epsilon_t^{\text{sh+}})) + w_6(L_\delta(\epsilon_t^{\text{sh-}})) \tag{2a}$$

where $\{u_t|\forall t \in \mathbb{H}\} := \{P_t^{\text{sh}}|\forall t \in \mathbb{H}\}$ is the set of control variables. The full optimal control problem includes a subset of the constraints formulated in Eq. (**??**). For the sake of conciseness, we do not detail them again.

Table 8: Experiment plan for exp2.

Title	Exp2: evaluation of SH modelling accuracy.
Research infrastructure	1) NEST backbone: medium-temperature grid; 2) devices listed in Table 9; 3) NEST REST API and OPC-UA.
Experiment realization	See Figure 3.
Experiment setup	See Table 9.
Experiment objective	The optimization objective is formulated in Eq. (2).
Precision of equipment	See Table 14.
Expected results	Room temperatures stay as close to the lower limit as possible and the controller preheats the room when an increase of the lower temperature limit appears in the horizon.
Suspension criteria	Results matching expectation and stable run of experiment for multiple days.

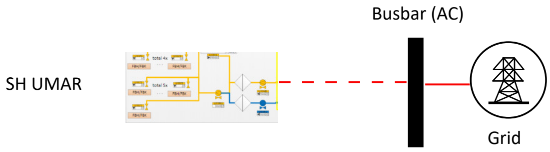

Figure 3: Single-line diagram of the electrical system configuration for exp2. The dashed line indicates a virtual electrical connection.

Table 9: List of devices included in exp2.

Name	Location	Number of Units
SH	NEST (UMAR)	2 bedrooms: 272, 274 and 1 living room: 273

3.3 Experiment plan: exp3

All the components except SH are involved in the experiment in order to test the integration of new devices such as DHW. Due to resource and time constraints, DHW is not tested in a standalone experiment. The objective is formulated as the total electricity cost minimization in Eq. (3) and detailed experiment plan is given in Table 10.

$$\underset{\{u_t|\forall t\in\mathbb{H}\}}{\text{minimize}} \quad \sum_{t\in\mathbb{H}}(r_t^{\text{b2g}}P_t^{\text{b2g}}+c_t^{\text{g2b}}P_t^{\text{g2b}})\Delta\tau_t+w_7L_\delta(\epsilon_t^{\text{dhw+}})+w_8L_\delta(\epsilon_t^{\text{dhw-}})+w_9((\epsilon_t^{\text{ev}})^2+(\epsilon_t^{\text{ebat}})^2) \tag{3a}$$

where $\{u_t|\forall t\in\mathbb{H}\}:=\{P_t^{\text{dhw}},P_t^{\text{ebat,ch}},P_t^{\text{ebat,ch}},P_t^{\text{ev,ch}},P_t^{\text{ev,ch}},P_t^{\text{pv}}|\forall t\in\mathbb{H}\}$ is the set of control variables. The full optimal control problem includes a subset of the constraints formulated in Eq. (**??**). For the sake of conciseness, we do not detail them again.

Table 10: Experiment plan for exp3.

Title	Exp3: a cost-aware energy management system.
Research infrastructure	1) NEST backbone: electrical grid, 2) NEST backbone: high-temperature grid, 3) NEST backbone: domestic water grid; 4) electrical devices listed in Table 11; 5) NEST REST API and OPC-UA.
Experiment realization	See Figure 4.
Experiment setup	See Table 11.
Experiment objective	The optimization objective is formulated in Eq. (3).
Precision of equipment	See Table 14.
Expected results	DHW temperatures stay as close to the lower limit as possible; building net power exchange has an opposite pattern to grid tariff.
Suspension criteria	Results matching expectation and stable run of experiment for multiple days.

3.4 Experiment plan: exp4

This experiment integrates all the devices and all the developed sub-functions. The objective is formulated as the minimization of the total equivalent carbon emission. The carbon intensity forecast is provided by aliunid and the readers are referred to Chapter 3 and Chapter 10.8 for more details. Shifting electricity consumption outside high carbon intensity periods can contribute to the national carbon-neutrality target.

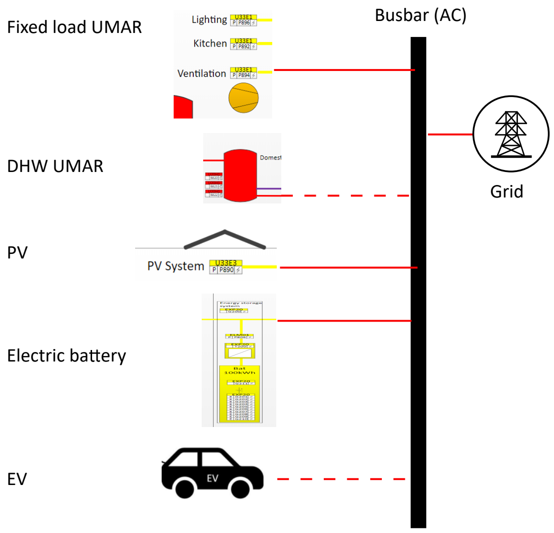

Figure 4: Single-line diagram of the electrical system configuration for exp3. The dashed lines indicate virtual electrical connections.

Table 11: List of devices included in exp3.

Name	Location	Number of Units
PV	NEST (dfab roof)	1
Battery	NEST	1
DHW	NEST (UMAR)	1
Fixed load	NEST (UMAR)	1
EV	Virtual	1

Table 12: Experiment plan for exp4.

Title	Exp4: an emission-aware energy management system.
Research infrastructure	1) NEST backbone: electrical grid, 2) NEST backbone: high-temperature grid, 3) NEST backbone: domestic water grid; 4) NEST backbone: medium-temperature grid; 5) electrical devices listed in Table 13; 6) NEST REST API and OPC-UA; 7) and aliunid's server for carbon intensity forecast.
Experiment realization	See Figure 5.
Experiment setup	See Table 13.
Experiment objective	The optimization objective is formulated in Eq. (**??**).
Precision of equipment	See Table 14.
Expected results	Indoor and water tank temperatures stay within predefined comfort zone; building net power exchange has an opposite pattern to the carbon intensity profile.
Suspension criteria	Results matching expectation and stable run of experiment for multiple days.

Table 13: List of devices included in exp4.

Name	Location	Number of Units
PV	NEST (dfab roof)	1
Battery	NEST	1
SH	NEST (UMAR)	2 bedrooms: 272, 274 and 1 living room: 273
DHW	NEST (UMAR)	1
Fixed load	NEST (UMAR)	1
EV	Virtual	1

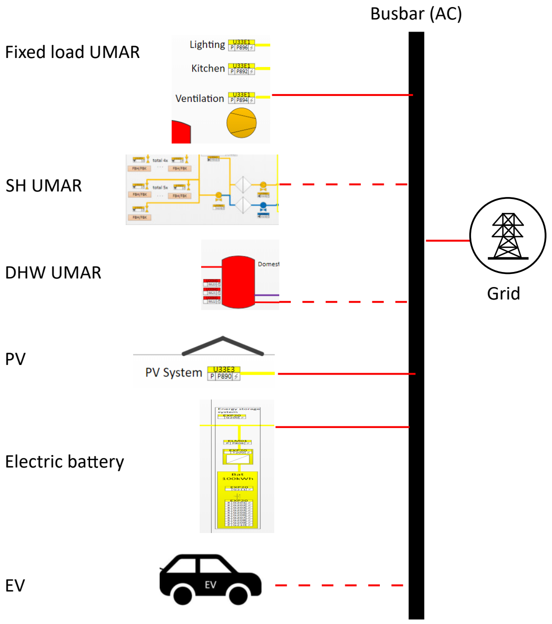

Figure 5: Single-line diagram of the electrical system configuration for exp4. The dashed lines indicate virtual electrical connections.

Table 14: Details on communication and actuation interfaces.

Component	Interface name	Unit	Resolution	Precision	Interface ID	Device ID	Right	Data source	Range
PV	active power	kW	15 mins	0.001	421110102	65NT_U33E3_T100	read	DB	0-7.32
Battery	active power	kW	15 mins	0.001	40200263	65NT_EXP20_G200	read	DB	[-]
	research mode reqst.	[-]	[-]	[-]	40200001	65NT_EXP20_G200	write	OPC-UA	0/1
	research mode status	[-]	15 mins	[-]	40200016	65NT_EXP20_G200	read	OPC-UA	0/1
	active power	kW	15 mins	0.001	40200005	65NT_EXP20_G200	write	OPC-UA	[-]
	SOC	%	15 mins	0.5	40200019	65NT_EXP20_G200	read	OPC-UA	39.5-57
UMAR 272	room temperature	°C	15 mins	0.15	42150288	65NT_U20R2_B870	read	DB	[-]
	research mode reqst.	[-]	[-]	[-]	42150483	65NT_U20R2_B870	write	OPC-UA	0/1
	research mode status	[-]	15 mins	[-]	42150295	65NT_U20R2_I870	read	OPC-UA	0/1
	set point	°C	[-]	[-]	42150484	65NT_U20R2_I870	write	OPC-UA	16/28
	input power	kW	15 mins	[-]	42150459	65NT_NTM31_P890	read	DB&OPC-UA	[-]
UMAR 273	room temperature	°C	15 mins	0.15	42150300	65NT_U20R3_B870_M00	read	DB	[-]
	research mode reqst.	[-]	[-]	[-]	42150487	65NT_U20R3_I870	write	OPC-UA	0/1
	research mode status	[-]	15 mins	[-]	42150307	65NT_U20R3_I870_D97	read	OPC-UA	0/1
	set point	°C	[-]	[-]	42150488	65NT_U20R3_I870	write	OPC-UA	16/28
	input power	kW	15 mins	[-]	42150459	65NT_NTM31_P890	read	DB&OPC-UA	[-]
UMAR 274	room temperature	°C	15 mins	0.15	42150312	65NT_U20R4_B870	read	DB	[-]
	research mode reqst.	[-]	[-]	[-]	42150491	65NT_U20R4_I870	write	OPC-UA	0/1
	research mode status	[-]	15 mins	[-]	42150319	65NT_U20R4_I870	read	OPC-UA	0/1
	set point	°C	[-]	[-]	42150492	65NT_U20R4_I870	write	OPC-UA	16/28
	input power	kW	15 mins	[-]	42150459	65NT_NTM31_P890	read	DB&OPC-UA	[-]
DHW UMAR	top temperature	°C	15 mins	0.01	42150242	65NT_U20H1_B820	read	DB	45-60
	middle temperature	°C	15 mins	0.01	42150244	65NT_U20H1_B821	read	DB	45-60
	bottom temperature	°C	15 mins	0.01	42150246	65NT_U20H1_B822	read	DB	45-60
	research mode reqst.	[-]	[-]	[-]	42150117	65NT_U20H1_I300	write	OPC-UA	0/1
	research mode status	[-]	15 mins	[-]	42150118	65NT_U20H1_M200	read	OPC-UA	0/1

	charge set point	℃	[-]	0.1	42150108	65NT_U20H1_I300	write	OPC-UA	0/1
	input thermal power	kW	15 mins	0.001	42150262	65NT_U20H1_P890	read	DB&OPC-UA	0$\sim$5.7
Meteo station	irradiance forecast	W/m^2	1 hour	0.1	402190002	DB	read	FTP server	[-]
	temperature forecast	℃	1 hour	0.1	402190000	DB	read	FTP server	[-]
	measured irradiance	W/m^2	15 mins	1	42160159	65NT_MET51	read	DB	[-]
	measured temperature	℃	15 mins	0.1	3200000	65NT_MET51_B870	read	DB	[-]
Fixed load UMAR	active power	kW	15 mins	[-]	42150423	65NT_U20E1_P001	read	DB	[-]
Carbon intensity	day ahead forecast	gCO_2 eq/kWh	15 mins	[-]	[-]	[-]	read	aliunid's server	[-]

4 Algorithms

4.1 Pseudo-code for implementation

Algorithm 1

```
procedure INITIALISATION
initialize:
    if black_start = True then
        user preference = default profile
    else
        user preference = user setting
    if com_status = OK then
        weather profile = forecast from MétéoSuisse
    else
        weather profile = default profile
    MPC controller ← user setting and weather profile
procedure CONTROL
loop:
    if opt_status = Enabled then
        execute Algorithm 2
    else
        execute Algorithm 3
    goto loop.
procedure ACTUATION
loop:
    if com_status = OK then
        publish
    else if connect_err = True then
        disconnect
        time.sleep(2)
        reconnect
        republish
    goto loop.
procedure FLEXIBILITY
    extract flexibility envelope according to Chapter ??
loop:
    if com_status = OK then
        send flexibility envelope
    else
        while time_out = False do
            try to resend flexibility envelope
            if com_status = OK then
                send flexibility envelope
                break;
```

goto *loop*.

Algorithm 2 MPC control algorithm

procedure CONTROL DECISION
    if *com_status* = OK **then**
        retrieve weather forecast from the database
        retrieve carbon intensity profile from the aliunid server
    else
        keep last update
    if *db_err* = True **then**
        use default/representative profiles
    else
        extract representative profiles from the database
    solve **??**
    set points ← *decision for the next time step*
    if *user_interact* = True **then**
        MPC controller ← *new user setting*
    else
        MPC controller ← *last user setting*
    if *user_withdraw* = True **then**
        stop flexibility provision

Algorithm 3 Benchmark control algorithm

procedure CONTROL DECISION FOR BATTERY
    if $P_t^{\text{pv}} < 0$ **then**
        $P_t^{\text{ebat,ch}} = -P_t^{\text{pv}}$
    else
        $P_t^{\text{ebat,ds}} = \max\{-\sum_{i \in D/\text{ebat}} P_t^i, -\overline{P}^{\text{ebat}}\}$
procedure CONTROL DECISION FOR OTHER DEVICES
    if *state* >= up_limit **then**
        maximum power
    else if *state* <= lw_limit **then**
        minimum power
    else
        continue previous action

In summary, we specify the details of the test and create guiding experiment plans to assist the experiment execution, diagnosis during the experiment and evaluation after the experiment.

References

[1] K. Heussen, C. Steinbrink, I. F. Abdulhadi, V. H. Nguyen, M. Z. Degefa, J. Merino, T. V. Jensen, H. Guo, O. Gehrke, D. E. M. Bondy, and Others, “Erigrid holistic test description for validating cyber-physical energy systems,” *Energies*, vol. 12, no. 14, p. 2722, 2019.

[2] Empa, “Nest wiki.” https://info.nestcollaboration.ch/wikipediapublic/. accessed: 12.12.2020.