

Energy Optimal Control of a Multivalent Building Energy System using Machine Learning

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Abstract: In this contribution we develop and analyse intelligent control methods in order to optimise the energy efficiency of a modern residential building with multiple renewable energy sources. Because of alternative energy production options a non-convex mixed-integer optimisation problem arises. For the solution we first apply combined optimisation methods and integrate it into a model predictive controller (MPC). In comparison, a reinforcement learning (RL) based approach is developed and evaluated in detail. Both methods, in particular reinforcement learning approaches are able to decrease energy consumption and keep thermal comfort at the same time. However, in this paper RL can achieve better results with less computational resources than MPC approach.

1 INTRODUCTION

Since buildings still account for about $\approx 35\%$ of Germany's primary energy consumption, the field of building automation and energy management has increasingly become a focus of current research (BMW, 2019). In addition to structural methods, such as improving building insulation, there is also a high saving potential that can be achieved by the building automation system itself. Considering the increasing use of varying renewable energy sources and storage systems, new methods such as model predictive control and machine learning based control approaches receive more and more attention (Renaldi, 2017 and Oldewurtel 2012). Especially algorithms from the field of reinforcement learning are particularly attractive (Chen, 2018 and Mason, 2019), since they pursue the goal of independent learning strategies in order to maximise a certain profit, whereby the short-term profit can be weighed against the accumulating long-term profit.

The central energy control system, also referred to as energy manager (EM), usually cannot access local controllers, such as control parameters of dedicated room controllers, in practice. Instead the EM should take higher-level, possibly binary, decisions. This includes the temporal on-off behaviour of certain energy consumers (demand-side management (Palensky and Dietrich, 2011)) or generators and

distributors (e. g. pumps or heatpumps). Mathematically, this results in (mixed-) integer optimisation problems with a large number of decision variables, that often can not be solved in reasonable time. Thus, intelligent mathematical approaches are needed, that are also applicable to a large number of energy producers and consumers in practice. In the last years the authors have analysed and developed several approaches in order to design and implement energy saving control algorithms for both heat/energy consumption and generation system. These used methods include simulation-based design and optimisation (Seidel, 2015), model-predictive control (Paschke, 2016) as well as data analysis (Paschke, 2020) for predictive maintenance and condition monitoring.

In this contribution we focus on the design of an energy management system for a modern residential building, with multiple renewable sources and storage systems. Thus, we will first introduce a model of the energy system of the building. In the subsequent section, for the design of the energy manager the decision variables and the constraints of the optimisation problem will be stated. Section 4 and 5 describe the implementation details of a model predictive control and a reinforcement learning based control methods, respectively. Finally, both approaches will be compared in Section 6 and a summary and an outline of future work will be

presented.

2 MODELING OF THE BUILDING ENERGY SYSTEM

The model of the building energy system is used as the process model of the designed energy manager. It is based on a 2007-built residential building, but was simplified in order to reduce runtime for simulation and optimisation. The real-world building is a detached house with 2 floors and around 300m² living space. It is composed of the following subsystems (see Fig. 1) for heat generation, buffering and consumption:

Solar Thermal System. A solar thermal system (STS) is installed on the roof of the building that can heat up the water in one of the two buffer tanks. The STS has a simple local control system that enables the pump of the collector if an adjustable temperature difference between the collector and the buffer tank is exceeded. The volume flow is controlled depending on the difference between the flow and return temperature. The STS can be activated and deactivated by the EM.

Geothermal System. The base load of the heat supply is provided by a brine-water heat pump (HP) with a ground heat collector. The environmental heat extracted by the heat pump is buffered also in these two heat storage tanks. The temperature in the storage tanks is controlled by bang-bang control, thus the heat pump is switched on if the temperature in one of the tanks falls below its desired value. The tanks are filled alternately.

Thermal Storages. As mentioned previously, the energy system of the building has two buffer tanks. The tanks provide heat for the building and have a volume of 1250l each. Because of the small size a frequent recharge is necessary, especially in winter.

Building and Automation System. The building model consists of one storey with two 100m² thermal zones that are oriented north and south, respectively. Occupancy and internal loads have been neglected. The zones are heated by a floor heating system that is controlled by two autonomous controllers. The temperature setpoints of 21 and 23°C are lowered by 1K depending on the daytime and weekday.

2.1 Environment

Weather data, such as outside temperature and solar

radiation, from a test reference year (TRY) of Dresden has been used as input to the model.

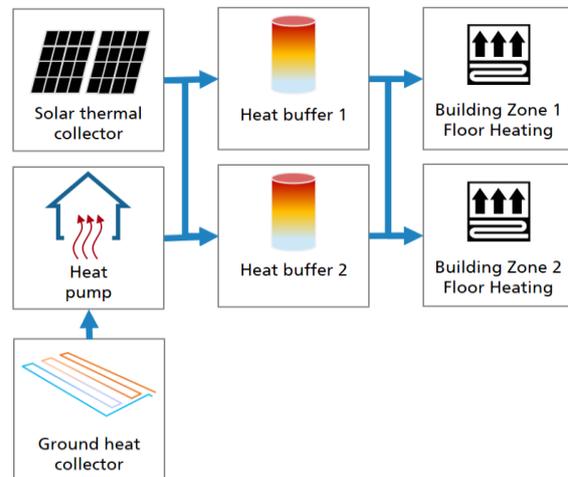


Figure 1: Structure of the building heating/energy system.

2.2 Simulation

The model of the building and the energy system was implemented and simulated with SimulationX of ESL. The energy system was modelled with the GreenCity-Library, whereas the local controllers of the STS and HP were implemented with the Modelica Standard Library (MSL). The energy system was modelled such that no EM is necessary, meaning that the task of providing heating energy to the building can be accomplished by the local controllers as well. This scenario corresponds to a standard approach, where the heat demand is covered by the STS and HP together, which can be inefficient if for example the HP is switched on although the STS can provide enough heat. These inefficiencies are addressed by the subsequently described optimisation approaches that are validated using the described model.

2.3 Implementation of MPC and RL

The development of complex control algorithms, such as MPC and RL, is not possible within SimulationX. Hence, an export of the whole model is necessary so that it can be accessed by external software. Thus, using the FMI Standard (Blochwitz, 2011), the model was exported into a Functional Mock-Up Unit (FMU). The implementation of the MPC and RL-based control algorithms was then done using Python and FMPy (Dassault Systems, 2017), that provides an interface for the import and execution of the FMU.

3 ENERGY MANAGER

According to the model of the building energy system, the high level building energy manager which we design is going to make three decisions: 1. Selection of the appropriate heat source for energy production; 2. Selection of the thermal storage to save the produced energy; 3. Selection of the thermal storage for heating. More precisely, the following discrete control inputs need to be determined:

- α_{HP} : Enable-signal for heat pump to use the geothermal system
- α_{Sol} : Enable-signal for solar heat
- $\beta_{HPs1}, \beta_{HPs2}$: Load thermal storage 1 or 2 with heat from heat pump
- $\beta_{Sols1}, \beta_{Sols2}$: Load thermal storage 1 or 2 with solar heat
- γ_1, γ_2 : Signals to discharge thermal storage 1 or 2 for heating.

This leads to the control input vector

$$\mathbf{u} = (\alpha_{HP}, \dots, \gamma_2)^T.$$

For a given time horizon T , the energy manager has to propose a control input function $\mathbf{u}(t)$, where $0 < t < T$, or $\mathbf{u}(k), k = 0, \dots, K - 1$, if T is divided into K discrete time samples.

Since each of the 8 control inputs are Boolean, for K time samples, there are $2^{8 \times K}$ possible solutions for $\mathbf{u}(k)$. In addition, there are some constraints to be considered. They are based on the real system configuration and are listed in Table 1.

Table 1: Constraints.

Only one storage shall be used for heating.	$\gamma_1 \neq \gamma_2$
Solar heat can be used to load both thermal storages	$\alpha_{Sol} \text{ XAND } (\beta_{Sols1} \vee \beta_{Sols2})$
Thermal storage 1 shall not be charged via heat pump.	$\alpha_{HP} \wedge \beta_{HPs2} \wedge \overline{\beta_{HPs1}}$
* For particularly cold days, both storages can be charged via heat pump and both can be used for heating at the same time.	$\alpha_{HP} \wedge \beta_{HPs1} \wedge \beta_{HPs2} \wedge \gamma_1 \wedge \gamma_2$

3.1 Optimisation Problem

For a concrete cost function J , we can note the following general discrete optimisation problem:

$$\begin{aligned} & \min_{\mathbf{u}(0), \dots, \mathbf{u}(K-1)} J(\mathbf{x}) \\ & \text{with } F(\mathbf{x}, \mathbf{u}(k), t) = 0 \text{ (Model)} \\ & \mathbf{g}(\mathbf{u}(k)) \geq \mathbf{0} \\ & \mathbf{h}(\mathbf{u}(k)) = \mathbf{0} \\ & \mathbf{u}(k) \in U = \{0, 1\}^8, k = 0, \dots, K - 1. \end{aligned} \quad (1)$$

Here F describes the model of the building energy system, \mathbf{g} and \mathbf{h} represent the constraints to be considered where according to Table 1 their concrete functions only depend on \mathbf{u} , not on \mathbf{x} .

For the cost function two main factors are taken into account:

1. Comfort violation.

In this paper comfort violation is indicated by the deviation of the room temperature T from the set temperature T_{set} . The set temperature values depend on the hour of the day and the weekday. A simple choice for cost calculation is:

$$b_i = (T_i - T_{i,set})^2 = e_i^2, \quad i = 1, 2, \quad (2)$$

where T_i is the temperature of the i -th thermal zone.

Considering the concept of thermal comfort (Gao, Li and Wen, 2019), which subjectively reflects the satisfaction of people under certain thermal conditions, such as too cold, cold, neutral, warm and too warm, the extent of temperature deviation e_i can also be punished differently as follows:

$$b_i = \begin{cases} 0, & e_i \geq 0 \\ 1, & -0.1 < e_i < 0 \\ 2, & -0.3 < e_i \leq -0.1 \\ 3, & -0.5 < e_i \leq -0.3 \\ 4, & -1 < e_i \leq -0.5 \\ 5, & -2 < e_i \leq -1 \\ 6, & -2 \leq e_i \end{cases} \quad (3)$$

In particular, we do not punish the case where the temperature is above the set temperature, since the building energy system does not have active cooling.

For both kind of cost definition, if temperature is given as vectors \mathbf{T}_1 and \mathbf{T}_2 of length N , the comfort cost can then be calculated as the sum of all N b_i -elements:

$$B_i = \sum_j^N b_{i,j}(e_{i,j}), \quad i = 1, 2, \quad (4)$$

or be calculated from the average value \tilde{T}_i of the vector \mathbf{T}_i :

$$B_i = b_i(\tilde{e}_i), \quad \tilde{e}_i = \tilde{T}_i - T_{i,set}, \quad i = 1, 2. \quad (5)$$

2. Electrical energy E_{el} .

Here we consider the electrical power consumed by the pumps (e.g. heat pump and pump of solar thermal system) for heating. This contradicts the first target of minimizing comfort violation. So for optimisation a trade-off of both targets is pursued.

Therewith, we have

$$J = w_1 B_1 + w_2 B_2 + w_e E_{el} \quad (6)$$

where w_1 and w_2 and w_e are the weighting factors.

Since the general optimisation problem formulated in eq. (1) is discrete with integer optimisation variables, we have a so-called constrained integer nonlinear problem, which belongs to the class of mixed integer nonlinear problem (MINLP).

3.2 Solution Approach

For a general MINLP there are different state-of-the-art solution approaches, e.g. the use of regularisation techniques where the exact knowledge of model equations is required (Mynttinen, 2015), optimisation methods combining constraint programming and nonlinear optimisation programs especially for scheduling problems (Wigström and Lennartson, 2012 and 2014), and complex heuristic optimisation methods (Schlüter et Al, 2009).

In this paper, based on the concept from (Wigström and Lennartson, 2014), we designed a solution approach which at first simplifies problem (1) using constraint programming technique, such that at the second step, a less complex optimisation strategy can be applied.

Constraint programming (CP) is generally used to find solutions of a problem with declarative stated constraints. It can be applied in our case as a first step to find those solutions of $\mathbf{u}(k)$ satisfying the nonlinear constraint equations. Here we take advantage of the fact that the constraint functions \mathbf{g} and \mathbf{h} according to Table 1 do not depend on internal states \mathbf{x} of the building. With an appropriate CP-solver, the solution space of problem (1) can be reduced: $\mathbf{u}(k) \in \tilde{U} \subset U$. Without regard to last constraint (*) only 16 feasible solutions instead of $2^{8 \times K}$ remain. The case (*) can be taken into account if the charge of both storages via heat pump and the simultaneous discharge of both is allowed. This additional solution can be added to \tilde{U} .

As a result, problem (1) can be simplified to an integer optimisation problem without constraints:

$$\min_{\mathbf{u}(0), \dots, \mathbf{u}(K-1)} \tilde{J}(\mathbf{x}, \mathbf{u}(0), \dots, \mathbf{u}(K-1)) \quad (7)$$

$$\mathbf{u}(k) \in \tilde{U}, k = 0, \dots, K-1$$

where \tilde{J} summarizes J and the building model F . This remaining problem needs to be linked with an appropriate solver and integrated into the energy manager for the control of the active building heating system.

In this paper we investigate two control strategies. The first is to integrate the optimisation problem stated above into a classic model predictive control where problem (7) can be solved by an appropriate heuristic optimisation method. The second is to use machine learning approaches, in particular, we have our focus on reinforcement learning. Both approaches are presented in the following sections.

To evaluate the benefits of these approaches, we compare their results with the behaviour of the basic building automation system where constraints from Table 1 are neglected. In that case the heat pump is activated according to the temperature level of each of the storages (here storage 1 can always be loaded via heat pump) and both storages are simultaneously and equally used for heating. This basic building control configuration will be subsequently denoted as NC (for no high level control).

4 MODEL PREDICTIVE CONTROL

4.1 Implementation

In case of MPC the optimisation problem (7) needs to be solved repeatedly at each time step for upcoming time horizon. In this paper, a simple form of genetic algorithm (GA) is applied as the optimisation solver. In order to determine appropriate optimisation parameters, e.g. population size, number of generations and weighting factors, a parameter variation study has been conducted.

The model predictive control is implemented in Python where the building model is integrated as FMU. For first analysis the FMU serves not only as the prediction model within MPC, but also as simulation model for obtaining building state. The time horizon is set to 24h and the time step is set to 3h in order to reduce the optimisation effort. This is acceptable insofar that the energy system is sufficiently slow. However, for dealing with fast changing environmental changes, the time step needs to be reduced in future.

Moreover, we compare the results using different comfort calculations given by eq. (2) denoted as R1 and eq. (3) denoted as R2, using eq. (4).

4.2 Simulation Result

In Fig. 2 – 4 the power consumption and the temperature of both thermal zones for 7 days in february (starts from Thursday) are presented for MPC and NC. Both versions of MPC with different comfort cost calculation can reduce the power consumption of the energy system of around 8% for R1 and 6,29% for R2. Also the comfort level can be improved.

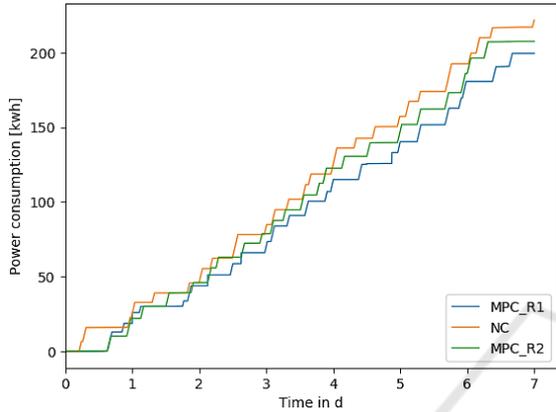


Figure 2: Comparison of total electric power consumption between NC, MPC_R1 and MPC_R2.

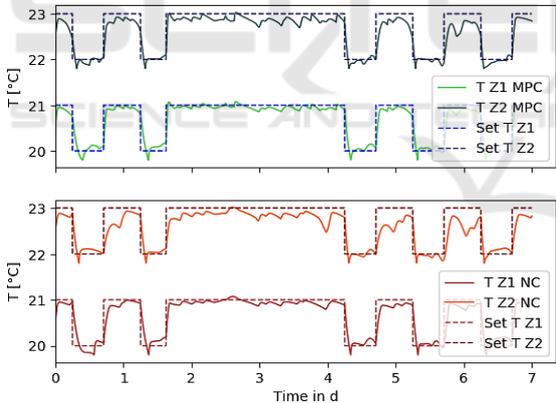


Figure 3: Temperature in zone1 (Z1) and zone 2 (Z2). top: MPC_R1, below: NC.

The energy saving is due to less charging of both thermal storages by heat pump while still covering the energy demand of both thermal zones. In particular, the average soc of both storages has been reduced compared to soc-level from NC. In case of R2, the soc for storage 1 and 2 are 19% and 6% less compared to NC (see Fig. 5).

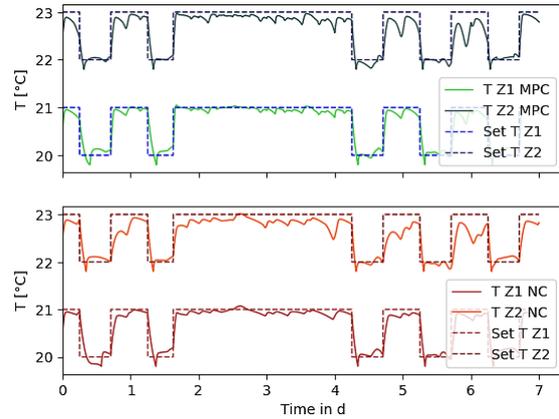


Figure 4: Temperature in zone1 (Z1) and zone 2 (Z2). top: MPC_R2, below: NC.

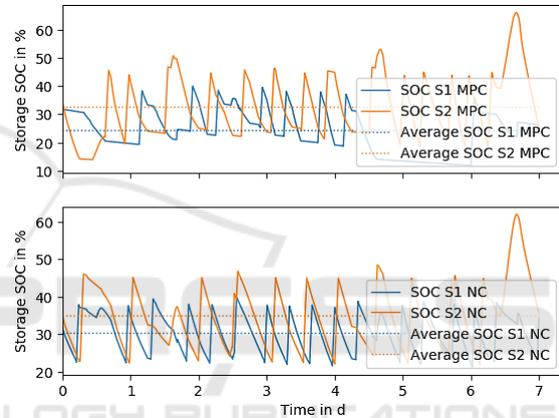


Figure 5: State of charge in S_1 and S_2 , top: MPC, below: NC.

This result is of course based on the ideal setting that the prediction model is exact. Moreover, eventhough the potential of such a high level energy manager with MPC is obvious, the computational effort and hardware demand of online optimisation cannot be neglected, especially when dealing with more complex energy systems. Therefore, in the next section, we will analyse and evaluate the application of reinforcement learning where such an online optimisation is not needed.

5 MACHINE LEARNING APPROACHES

As a subset of artificial intelligence (AI) machine learning (ML) is concerned with how to construct computer programs that automatically improved with experience (Jordan and Mitchell, 2015). Unlike the conventional rule-based programming these

approaches use sufficient data and algorithms to “train” the machine and make it capable to complete tasks by themselves.

5.1 Reinforcement Learning

Reinforcement learning (RL) is a form of ML, which is appropriate in solving complex optimal control problems above through the interaction between controller (AI agent) and system (environment). The agent learns by trial and error and is rewarded for taking desirable actions in a dynamic environment so as to maximize cumulative rewards (Sutton and Barton, 2018). Among all the perspectives on RL algorithms we focus on the commonly used model-free algorithms Q-learning and SARSA.

5.1.1 Markov Decision Process

We formulate the thermal comfort control and energy optimisation of the building as Markov Decision Process (MDP), which consists of a set of states S and actions A , transition probability function P , reward function R and the discount factor γ . Since the interaction involves a sequence of actions and observed rewards in discrete time steps $t = 0, 1, 2, \dots, T$ (the sequence is fully described by one episode), the agent observes at each step the current state ($s_t \in S$) of the environment and decides on an action ($a_t \in A$) to take next according to a selection policy $\pi(a_t|s_t)$. Which state the agent will arrive in is decided by $P(s_{t+1}|s_t, a_t)$. Once an action is taken, the environment delivers an immediate reward $r_t = R(s_t, a_t)$ as feedback. These steps will be iterated during the learning phase and the control policy will be updated until it is converged. Our purpose is to find the maximum of the future reward over the episode, which can be typically represented by the optimal Q value (Szepesvári, 2010).

State. The relevant state of the MDP in this case is occupation of the room, state of charge of the thermal storage tank S_1 and S_2 and ambient temperature T^{out} at each time slot, represented as:

$$s_t = (OP_t, T_t^{out}, SOC_t^{S_1}, SOC_t^{S_2})^T. \quad (8)$$

Action. The action of the MDP is equivalent to the inputs signals u of the system in section 3.

Reward. The reward of the MDP can be calculated as the opposite of the cost function J in section 3:

$$R = -J = -(w_e E_{el} + w_1 B_1 + w_2 B_2). \quad (9)$$

In the following, the reward function resulted from comfort cost definition (eq. (3)) will be noted as R_1 , and from temperature difference definition (eq. (2)) as R_2 , with eq. (5) for vectors.

Value Function. The estimated future reward in a given state, also known as return, is a total sum of discounted rewards going forward, mathematically represented as follow:

$$G_t = \sum_{k=0}^{\infty} \gamma^k \cdot r_{t+k+1}. \quad (10)$$

The discount factor $\gamma \in [0, 1]$ penalizes the rewards in the future, that may have a higher uncertainty and does not provide immediate benefits.

The expected return can be represented as an state-action value function/Q-function:

$$Q_{\pi}(s, a) = \mathbb{E}_{\pi}[G_t|s, a], \quad (11)$$

which can be decomposed into the immediate reward plus the discounted future values by *Bellmen equations*, and further by following the policy π :

$$\begin{aligned} Q_{\pi}(s, a) &= \mathbb{E}_{\pi}[r_{t+1} + \gamma \cdot Q_{\pi}(s_{t+1}, a_{t+1})] \\ &= r_{t+1} + \gamma \cdot \sum_{s_{t+1}} P(s_{t+1}|s_t, a_t) \\ &\quad \cdot \sum_{a_{t+1}} \pi(a_{t+1}, s_{t+1}) Q_{\pi}(s_{t+1}, a_{t+1}). \end{aligned} \quad (12)$$

Temporal-Difference Learning. Since the agent doesn't know the state transition function P before the learning phase, we can't solve the MDP directly applying *Bellmen equations*, but using temporal difference (TD) learning, which provides the agent with a method to learn the optimal policy implicitly. The value function Q will be updated towards the estimated return $r_{t+1} + \gamma \cdot Q(s_{t+1}, a_{t+1})$, mathematically represented as follow:

$$Q(s_t, a_t) = Q(s_t, a_t) + \alpha [r_{t+1} + \gamma \cdot Q(s_{t+1}, a_{t+1}) - Q(s_t, a_t)], \quad (13)$$

where $\alpha \in [0, 1]$ is the learning rate, which controls the extent of the update.

Selection Policy. The state transition in this case is stochastic and the optimal policy in current state s will select whichever action maximizes the expected return from starting in s . As a result, if we have the optimal value Q^* , we can directly obtain the optimal action $a^*(s)$:

$$a^*(s) = \pi^* = \operatorname{argmax}_{a \in A} Q^*(s, a). \quad (14)$$

It's common to balance the frequency of exploring and exploiting actions with the ϵ -greedy strategy, which chooses a randomly selected action with probability $\epsilon \in [0, 1]$ and otherwise according to eq. (14).

5.1.2 Control Strategy

SARSA (eq. (15)) and Q-learning (eq. (16)) are two of the classic algorithms using TD learning (eq. (13)).

$$Q^{new}(s_t, a_t) \leftarrow Q^{old}(s_t, a_t) + \alpha[r_{t+1} + \gamma \cdot \max_{a \in A} Q(s_{t+1}, a_{t+1}) - Q^{old}(s_t, a_t)] \quad (15)$$

$$Q^{new}(s_t, a_t) \leftarrow Q^{old}(s_t, a_t) + \alpha[r_{t+1} + \gamma \cdot \max_{a' \in A} Q(s_{t+1}, a') - Q^{old}(s_t, a_t)] \quad (16)$$

The key difference between SARSA and Q-learning is that Q-learning is an off-policy but SARSA an on-policy. It means that the Q-learning agent doesn't follow the current policy to pick the next action. It estimates the optimal Q^* , but the action a^* which leads to this maximal value may not be followed in the next step.

5.2 Implementation

The proposed RL algorithms were implemented in Python. The complete multivalent building energy system was integrated as FMU.

At the beginning of each episode, the FMU model will be instantiated anew and the initial states and as well as all variables and parameters required by the RL agent from the building environment will be obtained. The state-action space is represented as a $S \times A$ matrix, i.e. Q table, which starts with a zero matrix. During the training procedure the RL agent can improve the control strategy based on the update of the Q value in this table.

5.3 Simulation Result

5.3.1 Experimental Setup

In order to make all possible situations during the training occur, in other words, to fill the blank initial Q table, we train the model for a period of the whole year (from 1st January until 31st December), and the training episodes are set to 100. The first 7 days in February are used to test the performance of the energy management. The simulation step size for the model internal is set to 5 minutes and the duration of each time slot for the RL algorithm within one training episode is 30 minutes. Additionally, the hyperparameters settings such as learning rate α , discount factor γ , exploration rate ϵ and the weighting factors are varied between Q-learning and SARSA. The adjustment of these hyperparameters is performed manually and the final selection is listed in Tab.2.

Table 2: Selection of the hyperparameters.

	ϵ	γ	ϵ	w_e	w_1	w_2
Q-learning	0.95	0.9	0.6	1	150	150
				1	20	25
SARSA	0.5	0.8	0.6	1	150	150

Besides that, the performance of our RL algorithms is compared respectively with a default scenario using static control/baseline approach, precisely, a dummy agent with fixed action/control inputs that are all set to true.

5.3.2 Performance Comparison

As mentioned before, the main objective of RL agent is to maximize the obtained rewards, however the stability of the control policy is also essential. This means that once the algorithm has converged the reward should level off within a range. Figure 6 shows for example the rewards of the Q-learning algorithm throughout the learning phase within 200 episodes. We can observe that the received reward gradually increases in the first 100 episodes and keeps relatively stable thereafter.

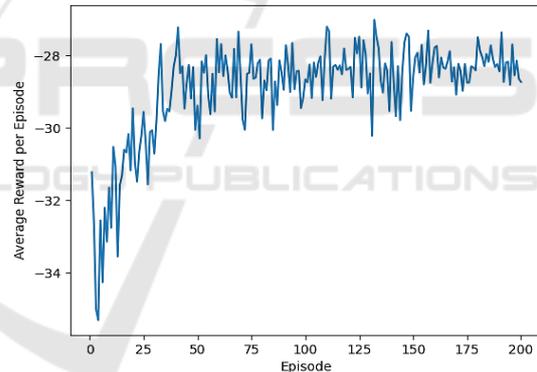


Figure 6: Reward during the training phase.

The comparison of total electricity cost of Q-learning and SARSA algorithms as well as the baseline approach/normal control (marked as NC in the figures) for the whole year and for one week are illustrated in Fig. 7 and Fig. 8. The percentage of cost reduction is also annotated. We can see that Q-learning with the reward function R_1 achieves the most effective saving 26.72% of the electrical energy consumption over the test week and 30.28% over the year. The reduction of the energy consumption distribute mainly in spring and autumn, because the sufficient solar thermal energy is available during these seasons. Thus it will be used more often than the heat pump. Furthermore, the saving is mainly achieved by a lower charge of the both thermal

storage tanks. Figure 9 shows that the average charge level of the thermal storage tank S_1 and S_2 is for example under Q-learning 26.88% and 30.01%, while without RL algorithm, namely with the normal control this argument is 34.44% and 33.94%, respectively.

In addition, the indoor temperature in the two-zone building under RL and NC approaches are illustrated in Fig. 10 - Fig. 12. We can see that our RL approaches ensure that the preset thermal comfort level is maintained and the difference between set point and actual temperature is minimal.

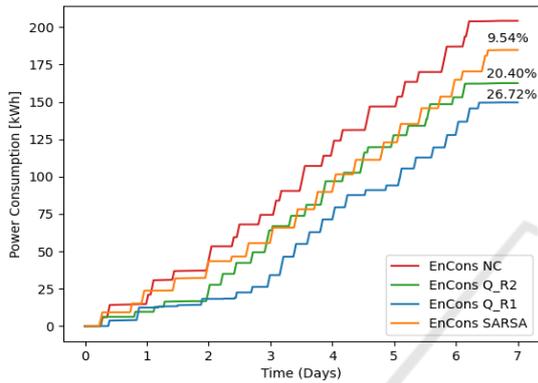


Figure 7: Comparison of total electrical Consumption one week.

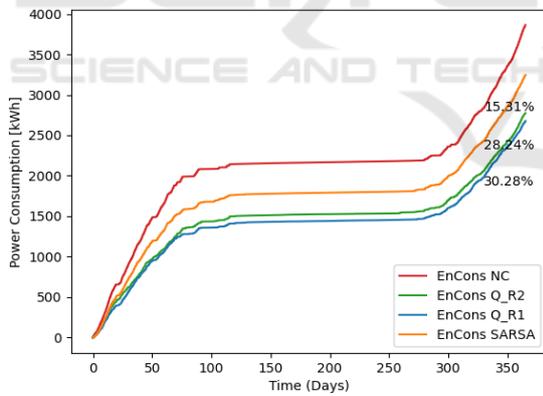


Figure 8: Comparison of total electrical consumption over the year.

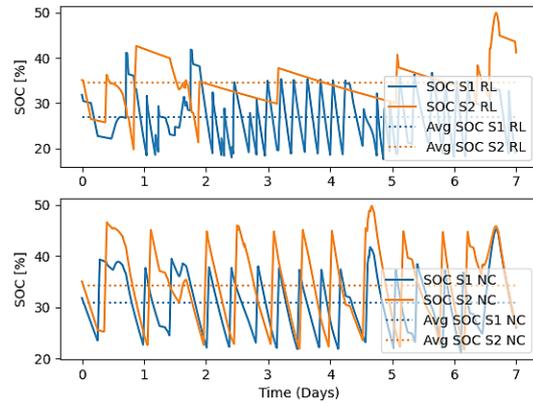


Figure 9: State of charge in S_1 and S_2 .

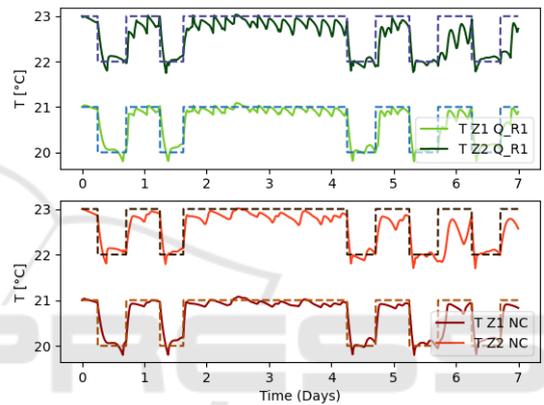


Figure 10: Temperature in zone 1 and zone 2 (Q_R1 vs. NC).

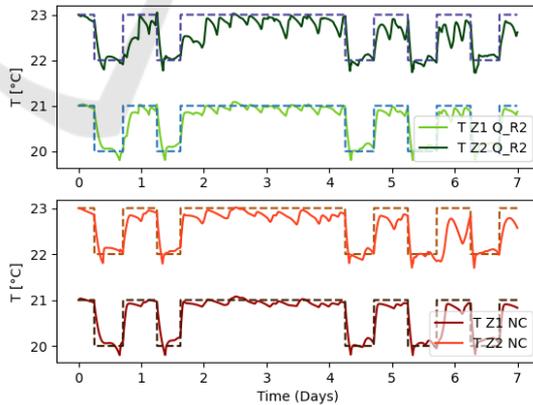


Figure 11: Temperature in zone 1 and zone 2 (Q_R2 vs. NC).

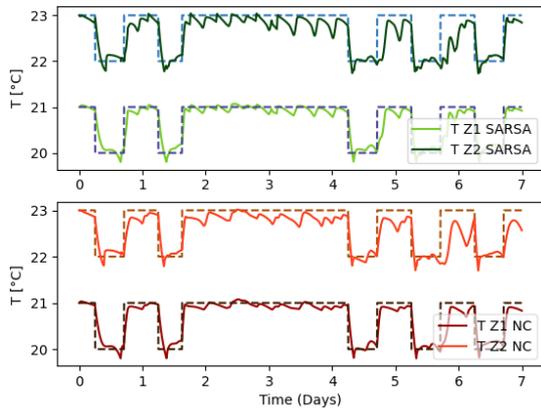


Figure 12: Temperature in zone 1 and zone 2 (SARSA vs. NC).

6 CONCLUSION

The simulation results presented in the sections above show that both control approaches MPC as well as RL are able to provide acceptable output for the energy manager. Both are capable of saving energy while maintaining comfort compared to the standard control algorithms. In particular, RL achieved better results. Compared to the results presented in (Seidel and Huang, 2020) the performance of the RL was improved. Further, compared with the successful applications of RL to home management systems mentioned from Mason, K. (Mason and Grijalva, 2019), our result of electrical energy saving are in accordance with the results from other researches.

In case of MPC, the heuristic optimisation method which is suited to this kind of discrete problems require much computational effort in order to get close to the optimal solution. Thus, corresponding resources such as powerful PC hardware are required. If the energy system grows and new system components or functions are added, the optimisation task would also become increasingly complex to solve. Further investigations are therefore needed to ensure the real-time capability of this control algorithms and to improve the cost-benefit ratio.

In contrast, RL with Q-table requires a learning phase before being commissioned as EM. During the online operation phase the required resources are relatively low and real-time capability is not critical since no simulation runs are required. Therefore, for the presented task of the energy manager, RL algorithm is a much more attractive approach. However, implementing the RL agent and especially the tuning of the hyperparameters during the learning phase is not straightforward. Thus, strategies for

setting the optimal hyperparameters need to be analysed in future works.

On the other hand, the teaching of the RL agent with the aforementioned models can be processed offline. Learning can also be continued during operation with sensor data from the real energy system so that an adaptation of the RL agents behaviour to the real energy system can be achieved and thus, further improvements of the results are possible. However, real-world learning must be done much more carefully since exploring new state-action combination could result in discomfort or waste of energy.

On the contrary, in case of MPC, a change within the energy system would require an adaption of the prediction model in order to obtain optimal results. Otherwise the output of the energy manager may not be acceptable. However, in order to achieve very good results right at the beginning of operation phase, an accurate system model is indispensable for both MPC and RL.

Another important difference between the two methods is the weighting of long-term gains. For the classic MPC optimisation, the time horizon in which an optimal solution must be found is fixed in general. The actions and the cost at each time step within the time horizon are equally weighted. For RL, the profit of the next action step has the biggest impact, while profits of future actions are weighted less according to the discount factor. Therefore the greater uncertainty of long-term forecasts can be taken into account.

In this paper, Q-Learning yields very good results for the energy system. In case of more complex systems and control tasks, it may be necessary to use more advanced methods of RL, such as deep learning with neural networks, which require much more training. For Q-tables, however, a few hundred episodes are sufficient to achieve good control results.

7 SUMMARY AND OUTLOOK

Classic MPC and RL were tested and compared for the high-level control of the energy system of a single-family house. In this paper RL can achieve better results than MPC with much less computational resources and is therefore suited for the online control of the building energy system.

Reinforcement learning thus offers attractive possibilities which the authors will continue to analyse in future works.

Moreover, we will take a deeper look at the optimization problem itself and especially the potential of multi-objective optimisation in the context of RL and MPC, since for complex energy systems, different and more conflicting goals will arise.

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