Increasing the Energy Flexibility of Buildings controlled by Model Predictive Control

Christian Karczewski [a], *Tobias Henzler* [a], *Konstantinos Stergiaropoulos* [a]

[a] Institute for Building Energetics, Thermotechnology and Energy Storage (IGTE), University of Stuttgart, Stuttgart, Germany, christian.karczewski@igte.uni-stuttgart.de

Abstract. The growth of renewable energy sources in the electricity grid and the electrification of heat generation in buildings using heat pumps increase the necessity of flexible consumers who can change their electric load. Operating the building in a flexible way means that the building's load is adjusted, e.g. to an electricity price. Model Predictive Control (MPC) is seen as a key algorithm in building energy management systems to provide the requested flexibility. In most studies covering energy flexible buildings, the load shifting is achieved by an economic MPC that uses an objective function, which aims to minimize the building's operating costs, assuming a variable electricity tariff. However, the most economic operating point corresponds in the heating period to the lower limit and in the cooling period to the upper limit of the thermal comfort band. As a result, the available flexibility that a building can offer is limited. In this work, a novel formulation of the control law, aiming to increase the energy flexibility of buildings, is derived and evaluated. From the current operating point, the heat pump's load for reaching the upper and lower comfort limit in the building is estimated. These two demand curves are used to determine a control signal that balances the trade-off between thermal comfort and operating costs whilst increasing the building's available flexibility. The proposed control strategy is evaluated on lumped-element models of German single-family houses, which are equipped with heat pumps, using the day-ahead electricity price as an incentive. Different indicators (e.g. power shifting capability and flexibility factor) are evaluated showing increased flexibility but also increased operating costs compared to classical economic MPC. Providing flexibility to the grid through demand response will require to operate the building at a point that is not cost-optimal. Higher operating costs on the building side would need future electricity contracts to include a flexibility refund in order to increase the building operator's willingness to provide flexibility.

Keywords. Energy Flexibility, Model Predictive Control, Building Climate Control, Heat Pump
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1. Introduction

The German electricity grid is subject to significant changes in both the generation and the consumption side. The generation side is affected by an increasing share of renewable energies, which is a result of the European Green Deal [1]. The hardly controllable and predictable nature of renewable energy sources, like solar radiation and wind, lead to a growing need for demand-side management. The building sector is a major consumer since it is responsible for approximately 40% of the primary energy use in the EU [1]. Most of the consumption is attributed to space heating, where heat is mainly generated through the combustion of fossil fuels. There is a rising share of heat pumps that is leading to an electrification of the heating sector and hence to increased stress on the electricity grid. As heat pumps couple the heating sector with the electricity grid, they will prospectively play a central role in demand-side management.

A high share of renewables in the energy system can only be reached if the installed capacity exceeds the consumption. However, this will result in a waste of electricity production [2]. Thus, additionally to energy efficiency, energy flexibility will be crucial [3]. The building's mass is capable of storing a high amount of energy, allowing to keep the indoor air temperature inside a comfort band for a certain period [4], while heat and cold supply systems are operated with an increased or decreased load. For instance, instead of curtailing wind parks, buildings equipped with heat pumps could increase their load and store thermal energy in the building's mass [5]. If Germany's single-family houses were equipped with heat pumps, an electrical load in the magnitude of up to 57 GW could be shifted through the exploitation of the thermal capacity of the building mass [4]. This load shifting potential is immense, considering that currently, Germany's yearly mean electricity demand is around 60 GW.

To exploit the building's energy flexibility intelligent control algorithms are necessary. Model Predictive Control (MPC) is an advanced control algorithm that is suitable for building climate control, being able to achieve an optimized operation in terms of user comfort, energy efficiency or operational cost [6].

This contribution discusses the disadvantages of a commonly used formulation of MPC for load shifting while simultaneously introducing a new approach that aims to increase the grid-oriented energy flexibility of buildings.

2. State of the art

In this section, the use of MPC for advanced building control is introduced first. Then, the state of the art in using MPC to exploit the energy flexibility in buildings is presented. Finally, the research gap and the contribution of this paper are highlighted.

2.1 Advanced building control

Intelligent buildings are independent entities that operate in a way, which ensures the building users' comfort needs whilst energy consumption is minimized. Additionally, intelligent buildings communicate with the grid and contribute to grid stability through demand response [7]. The building's energy management system controls the heating, ventilation and air conditioning systems and plays a central role in achieving the above-mentioned properties. MPC is an advanced control algorithm, that can be incorporated as a supervisory control strategy into the building's hierarchical control structure [8].

Through MPC, the controlled system is steered into the desired state by solving an optimal control problem. A process model is used to determine the system's future reaction whilst considering future disturbances. The optimal control signal is attained through the minimization of an objective function. The objective function defines the control objective, which can be for instance reference tracking or an economic operation. Additionally, systems states and control inputs can be constrained. [9]

If MPC is used for building climate control, the actuated values are mostly the heat flows into the building zones and the controlled values are the zone temperatures. Due to the building's large thermal mass and the related long time constants, MPC can outperform reactive controllers like PID controllers [8]. For example, MPC can preheat a building before the outdoor air temperature falls, thus keeping the indoor air temperature inside the comfort band. Numerous studies prove the potential of MPC in reaching common control objectives, like the maximization of user comfort, energy efficiency [10] or monetary savings [11]. As these targets are partly opposing, they need to be weighted if several of these are considered [12]. For further information on MPC in building climate control, the reader is directed to the extensive review by Drgoňa et al. [6].

2.2 Energy flexibility in buildings

The growing need for exploiting the energy flexibility of buildings led to the launch of International Energy Agency Annex 67 "Energy Flexible Buildings" [13] and the subsequent Annex 82 [14]. Flexibility is the capability to adjust a building's load profile, e.g. through load shifting in response to a price signal [15]. In order to exploit the building's energy flexibility, a control strategy is necessary. The identified mainly used control strategies are Rule-Based Control (RBC) and MPC [16].

The control law for RBC can be expressed with if-then statements or time schedules. Set point changes according to schedules enable load shifting. An example, already applied in the 1950s, is the use of electric storage heaters in off-peak periods [17].

In MPC the optimization targets are formulated more clearly than in RBC [16]. In terms of economic operation, MPC can achieve lower operating costs compared to RBC [18]. A review of control strategies for enabling energy flexibility in buildings reveals, that the cost-optimal formulation of MPC is a promising approach and thus being most commonly evaluated in scientific studies [5]. An Economic MPC (EMPC) aims to minimize operating costs in the prediction horizon. The incorporation of future energy prices (e.g. the day-ahead electricity price [19]) into the optimization leads to an increased load in low price regions and a decrease in high price regions. Although the main objective is to minimize costs, a load shift is achieved as a side effect.

Depending on the objective of exploiting the building's energy flexibility different Key Performance Indicators (KPIs) are used for the assessment. These are, among others, increased self-sufficiency [18], peak power reduction [18], monetary cost reduction [19] or the reduction of greenhouse gas emissions [20].

2.3 Research Gap – Increasing the grid-oriented energy flexibility

Exploiting the building's energy flexibility through EMPC seems favourable from the building operator's point of view, as it yields an economic benefit. Obviously, the biggest savings are attained if the electrical heat or cold generators are operated with full load in low price regions and turned off in high price regions. An aggregation of economically controlled buildings will cause fluctuations in the grid, making this approach questionable from the grid operator's point of view. To ensure grid stability, the authors in [21] propose buildings to be gridfriendly and grid-responsive. Thus, buildings should avoid putting additional stress on the grid and be able to change their demand according to the needs of the grid. The ability to change the demand requires buildings to provide grid-oriented flexibility which is composed of positive and negative flexibility, i.e. the demand can be increased and decreased.

EMPC can be used to exploit the building's flexibility in a grid-oriented way through adding optimization targets to the objective function like a load reference profile [22], [23]. In this way, a demand reduction is incentivised by the grid operator. An economical controller keeps the zone temperature at the lower limit in the heating period so that the zone needs to be preheated before the load can be reduced. However, the duration of the demand reduction is limited, as the indoor air temperature will fall quickly [22]. Operating a building in a way, where grid-oriented flexibility can be provided, results in increased operating costs [23].

To the knowledge of the authors, there is a lack of price-sensitive control approaches, which focus on increasing the building's available flexibility, both in the positive and negative direction. Therefore, the aim of this contribution is to introduce a novel, flexible control approach that enables the use of the building's flexibility according to a price signal.

3. Control law

In this section, the control law of the EMPC is introduced first. Next, a novel flexibility oriented control law based on MPC is presented.

3.1 Cost optimal control law

The general optimal control problem can be formulated in the following way [24]:

$$\begin{aligned} &u_{\mathrm{opt}}(\cdot) = \arg\min_{x(\cdot),u(\cdot)} J(x,u) \\ &\dot{x}(t) = f\big(x(t),u(t)\big) \\ &x(0) = x_0 \\ &x(\cdot) \in \mathcal{X}, u(\cdot) \in \mathcal{U} \end{aligned} \qquad (1)$$

The optimal control sequence $u_{\mathrm{opt}}(\cdot)$ minimizes the objective function $J(x,u)$, that is dependent on the control signal u and the system's states x. The minimization is executed with respect to the system model f, the initial state x_0 and constraints for the control inputs and states $\mathcal{U}$ and $\mathcal{X}$.

For the ease of finding a solution to the optimal control problem, quadratic objective functions are favourable. In the case of an EMPC, the cost-optimal formulation of the objective function is chosen as

$$J_{eco} = \left(\sum_{i=0}^{N-1} c(i) \cdot u_{\mathrm{el}}(i)\right)^2 \qquad (2)$$

with $c(i)$ being the time-dependent electricity cost and u_{el} being the electrical load of the heat or cold generator.

3.2 Flexibility oriented control

The flexibility oriented control law consists of a two-step approach. From the current operating point, the demand for reaching the upper and lower comfort limit in the building is estimated. The approach is applicable for the heating and cooling case. In the following, it will be presented exemplarily for the heating case.

As a first step, the electrical demand is estimated that is needed to reach an energetic efficient operating point while simultaneously discharging a possibly present thermal energy storage through solving

$$u_{\min} = \arg\min_{u(\cdot)} \alpha \left(\sum_{i=1}^{N} \left\| \vartheta_{s,min}(i) - \vartheta_s(i) \right\|^2\right) + \sum_{i=0}^{N-1} \left\| u_{el} \right\|^2 \qquad (3)$$

under the condition, that the indoor air temperature stays within the comfort boundaries. The storage temperature at each prediction step i is denoted by $\vartheta_s(i)$. The objectives of discharging the storage and minimizing the control input are weighted through the weight α. In the heating period, the vector sequence $u_{\min}$ corresponds to the electrical load of the heat generator and to heat flows into the zones that keep the building at its lower temperature limit. In the cooling period, $u_{\min}$ corresponds to the electrical load of the air conditioning units required to keep the building at the upper comfort limit.

As a second step, the electrical demand needed to reach the upper temperature limit in the building's zones and thermal storage is estimated. This is performed by solving

$$u_{\max} = \arg\min_{u(\cdot)} \sum_{i=1}^{N} \left\| \vartheta_{set}(i) - \vartheta(i) \right\|_{\mathrm{W}}^2 \qquad (4)$$

with $\vartheta(i)$ as the temperature vector composed of all building zones and the thermal storage. The weight matrix W is used to define which set point ϑ_{set} is to be reached first. The left plot in figure 1 depicts the qualitative course of the zone temperature as a result of the input sequences according to equations (3) and (4). The two energy lines in the right plot span the range in which the building can be operated flexibly.

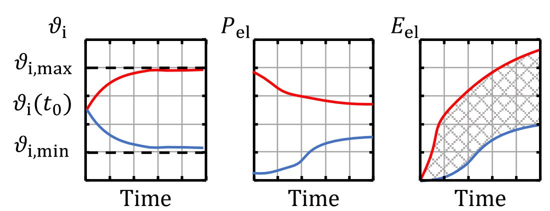

Fig. 1 – Schematic view of heating up (red lines) and cooling down (blue lines) the building. The plots show the indoor air temperature (ϑ_i), the electrical load of the heat generator (P_{el}) and the energy demand (E_{el}).

The current control signal, which keeps the buildings operating point inside the flexibility range is calculated through the control law

$$u_{\mathrm{Flex}} = (1-\rho)^2 \cdot (u_{\max} - u_{\min}) + u_{\min} \tag{5}$$

The flexible control input u_{Flex} is dependent on the normalized price signal ρ. A high price signal $\rho = 1$ causes the controller to keep the building in the energy efficient operating mode. A low price signal $\rho = 0$ results in an increased load. Thus, for the heating case, the room temperature will be increased and the thermal mass activated. The price is considered quadratically to dampen the increase of the load and to keep the building closer to the energy efficient operating point.

4. Case study

In this section, the thermal energetic building model is described, which is used to compare the operation of the flexible and the economic controller. The case study aims to show the negative flexibility of two exemplary German single-family houses that are equipped with heat pumps. The simulative model and setup are explained first. Then, the evaluation metrics used to quantify flexibility are presented.

4.1 Simulative model

A resistance capacitor network is able to describe the heat dynamics of a building adequately [25]. Two representative German single-family houses are considered, one equipped with a radiator for space heating and the second equipped with an underfloor heating system. The models are adapted from [4]. A second-order model with two temperature states describes the building with radiators:

$$\begin{aligned} C_i\dot{\vartheta}_i &= \frac{\vartheta_e - \vartheta_i}{R_{ei}} + \frac{\vartheta_a - \vartheta_i}{R_{ai}} + A_w\dot{Q}_{sol} + \dot{Q}_{Int} + \dot{Q}_h \\ C_e\dot{\vartheta}_e &= \frac{\vartheta_i - \vartheta_e}{R_{ei}} + \frac{\vartheta_a - \vartheta_e}{R_{ea}} \end{aligned} \tag{6}$$

The states are the indoor air temperature ϑ_i and the temperature of the building's envelope ϑ_e. Solar gains are denoted by $\dot{Q}_{sol}$, internal gains by $\dot{Q}_{Int}$, the outdoor air temperature by ϑ_a and the heat supplied by the heating system by $\dot{Q}_h$. The heat capacities of the states are denoted by C and the heat transfer resistances are denoted by R. The solar radiation enters the building through windows with the effective window area A_w.

Due to the high capacity of the heating system, the building with underfloor heating is described by

$$\begin{aligned} C_i\dot{\vartheta}_i &= \frac{\vartheta_e - \vartheta_i}{R_{ei}} + \frac{\vartheta_a - \vartheta_i}{R_{ai}} + \frac{\vartheta_f - \vartheta_i}{R_{fi}} + A_w\dot{Q}_{sol} + \dot{Q}_{Int} \\ C_e\dot{\vartheta}_e &= \frac{\vartheta_i - \vartheta_e}{R_{ei}} + \frac{\vartheta_a - \vartheta_h}{R_{ah}} \\ C_h\dot{\vartheta}_h &= \frac{\vartheta_i - \vartheta_h}{R_{hi}} + \dot{Q}_h \end{aligned} \tag{7}$$

The states in equation (7) are the temperatures of the indoor air ϑ_i, the building's envelope ϑ_e and the underfloor heating ϑ_h.

The building is equipped with an air-water heat pump with a continuously adjustable inverter. It is modelled as follows

$$\dot{Q}_{\mathrm{HP}} = COP \cdot P_{\mathrm{el}} \tag{8}$$

with COP being the coefficient of performance. This coefficient depends on the operating point of the heat pump. The COP is derived from [26] and can be expressed by

$$COP = COP_{\mathrm{fl}} \cdot PLF \cdot DOF \tag{9}$$

with COP_{fl} being the COP under full load, PLF being the partial load ratio and DOF being the defrost operation factor. Defrost is neglected in this work, i.e $DOF = 1$. The COP_{fl} and PLF are derived from standard data available in [27]. The COP_{fl} is dependent on the outdoor air temperature and the supply temperature in the circuit. In addition, the building is equipped with a thermal storage. The energy balance for the storage is

$$C_w V_s \dot{\vartheta}_s = \dot{Q}_{HP} - \dot{Q}_h \tag{10}$$

with the temperature of the storage ϑ_s and the volume of the storage V_s. The storage is assumed to be ideally mixed. Through a three-way mixing valve, a constant supply flow temperature is achieved in the space heating circuit. The temperature of the supply flow in the heat pump's circuit is set to 5 K above the storage temperature ϑ_s. The modelled system is depicted in figure 1.

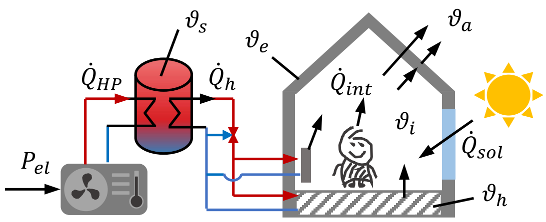

Fig. 1– Schematic view of the used model.

4.2 Simulative setup

Heat pumps are especially suitable for heating purposes if the supply temperature of the heating circuit is low. As the German stock of single-family houses is heterogeneous, two exemplary buildings are considered: The first is a retrofitted house, that has been built in the period between 1984 and 1994 and is equipped with radiators. The second building is constructed after the year 2016 and is equipped with an underfloor heating system. The lower storage temperature limit is set to the supply temperature of the heating system and the upper limit is set to 70°C. The heat pump is designed to meet the heating load of the building at an outdoor air temperature of -7°C for an indoor air temperature of 22°C. The model parameters are summarized in table 2 in the appendix. Weather data, namely solar radiation and ambient air temperature, is used for Stuttgart from the year 2019. The day-ahead electricity price for 2019 is used as a price signal. The price is transformed through a logistics function to the range $0 \le \rho \le 1$. The simulations are implemented in *MATLAB* and the open-source framework *acados* [24] is used for solving the optimal control problems.

4.3 Evaluation metrics

The flexible control aims to operate the building at a point at which the available flexibility is increased. To characterize the flexibility the following definition, adapted from [23], is used

$$\begin{aligned} \Phi^{+} &= l_{\max}(t) - l_{\text{ref}}(t) \geq 0 \\ \Phi^{-} &= l_{\text{ref}}(t) - l_{\min}(t) \geq 0 \end{aligned} \qquad (11)$$

with the reference load l_{ref}, the maximum and minimum load $l_{\max}$ and $l_{\min}$. The minimum and maximum load result from the operational limits of the heat or cold generators and the comfort band of the room temperature. For instance, if the room temperature is at the upper comfort limit in summer, the electrical load of an air conditioning unit cannot be decreased and the negative load change Φ^{-} equals zero. The energy, which can be shifted in an interval T is calculated by

$$\Psi_T^{+/-}(t) = \int_t^{t+T} \Phi^{+/-}(\tau)d\tau \qquad (12)$$

The total shiftable load substantially depends on the heating and cooling demand of the building. Therefore, the relative load shifting capability

$$\varphi_{rel,T}^{-} = \frac{\bar{P}_{el}}{P_{el,max}} = \frac{\Psi_T^{-}}{T \cdot P_{el,max}} \qquad (13)$$

is used. It describes the mean load that can be reduced in the flexibility interval T as a share of the maximum electrical load of the heat or cold generator $P_{el,max}$. To characterise the type of flexibility, the flexibility factor

$$FF = \frac{\Psi_T^{-}}{\Psi_T^{-} + \Psi_T^{+}} \qquad (14)$$

will be used. The denominator is the sum of the available positive and negative flexibility. If FF equals zero, the system can only increase its demand in the predicted horizon. If FF equals one, the system is operated at a point, where the system can only decrease its load.

5. Results and discussion

In this chapter, the differences in the operation modes of the flexible and economic control approach will be presented and discussed.

5.1 Results

First, the closed-loop behaviour of the buildings, which is shown in figure 2, is inspected in detail. The top graph shows the input variables, i.e. the outdoor air temperature and the normalized price signal. The electrical power of the heat pump, the indoor air and storage temperature are depicted in the following graphs. The last graph shows the available flexibility for the next 12 hours that is calculated by equation (12). During the first days, the price signal gradually falls, while the outdoor air temperature is rising from -2 to 7 °C. The lines belonging to the flexible controller are in blue, the ones belonging to the economic controller are in red.

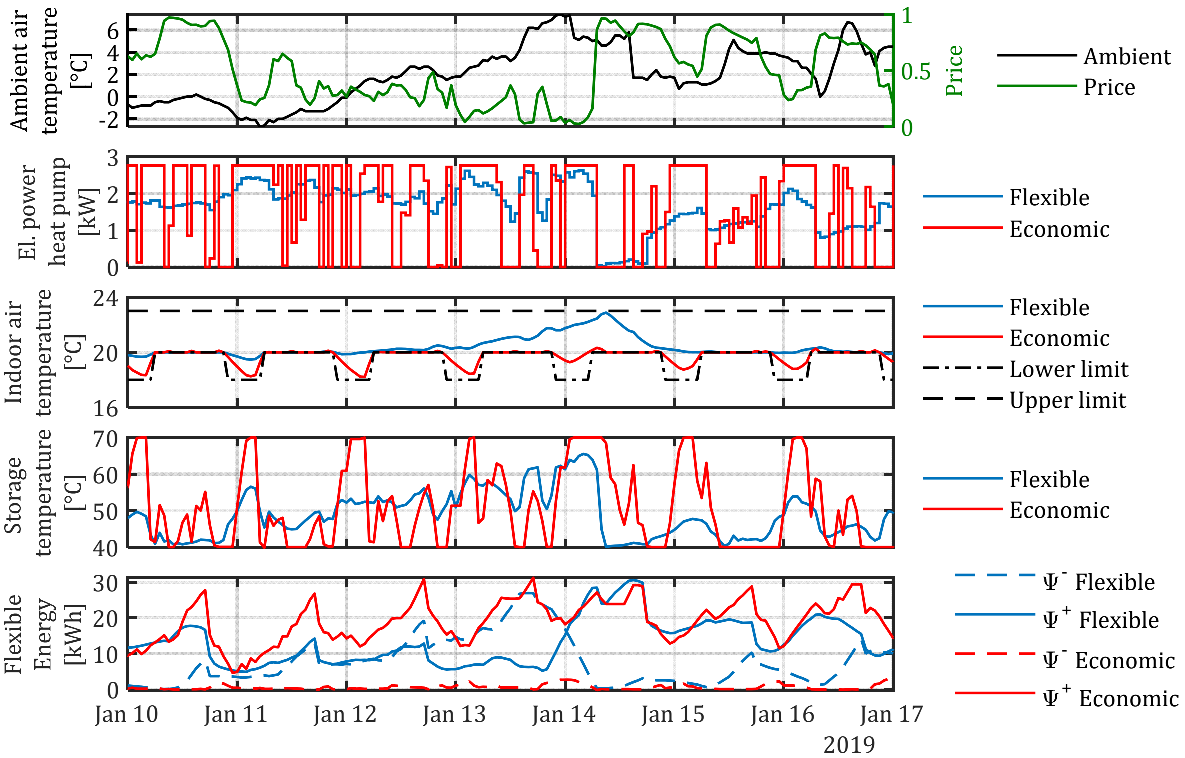

Fig. 2– Comparison of the closed-loop behaviour of a flexibly and an economically controlled building.

The economic controller keeps the indoor air temperature at the lower limit. The heat pump is primarily operated at full load during the local price minima, which causes an increase in the storage temperature. The heat buffered in the storage is drawn gradually to fulfil the building's heating demand. It is seen, that the economic controller mainly exploits the flexibility of the thermal storage. Due to the relatively large price step on the 14th of January, the heat pump is operated for a longer period. As soon as the storage is fully charged, the indoor air temperature is elevated, too. Due to the raise of the indoor air temperature, heat is stored in the thermal mass, which allows sustaining a higher temperature of the thermal storage for a longer time.

The flexible controller differs from the economic controller through a continuous operation of the heat pump. During the first days, while the price signal is falling, the storage temperature continuously rises. After the storage has reached a certain state of charge, the indoor air temperature is elevated additionally. At the time when the price step occurs, both the indoor air temperature and the storage temperature are close to the upper limit. After the price step, the storage is discharged first and then the indoor air temperature drops. It takes approximately two days for the indoor air temperature to reach the lower temperature limit again

The available flexibility differs in both cases. As the economic controller keeps the indoor air temperature at the lower comfort limit, the load of the heat pump cannot be lowered any further, without violating the users' comfort needs. This results in negative flexibility, that is close to zero throughout the depicted period. In return, the positive flexibility is significantly higher. The flexible controller operates the heat pump at a higher load than necessary, which allows storing heat in the thermal storage and the building mass. This can be seen especially during the night setbacks when the flexible controller does not let the building cool down completely. While the price is falling, the system is charged and positive flexibility is decreased, whereas negative flexibility is increased. When the price rises, the heat pump is operated at a significantly lower load for a longer time and the negative flexibility of the building is exploited. In the shown case, the flexible controller leads to a reduced operation of the heat pump for 11 hours after the price step, while the cost-optimal controller turns on the heat pump at full load after 6 hours again.

Next, the type of available flexibility for one year is analysed. Figure 3 shows the hourly distribution of the flexibility factor that is calculated through equation (14) for the heating period in dependence on the outdoor air temperature and the 12 hours mean value of the future price signal. The flexibly controlled building's flexibility factor reaches from 0 to 1 and is dependent on the price signal. As expected, the available flexibility for low future prices is of negative type (i.e. FF close to 1). The flexibility factor of the building controlled by an EMPC is mainly in a range from 0 to 0.25, which indicates that only a small fraction of the building's flexibility is negative.

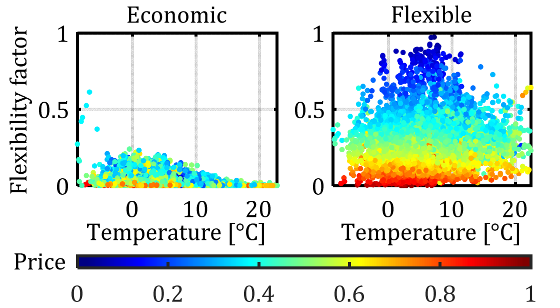

Fig. 3– Comparison of the flexibility factor for the two control approaches. Left plot: economic control, right plot: flexible control.

Figure 4 shows the mean total flexibility. The bars are divided into the type of flexibility. The building equipped with underfloor heating has a mean total flexibility of 21 kWh for the prediction horizon of 12 hours. The total flexibility of the economically controlled building is slightly higher than of the flexibly controlled building. The flexibly controlled building shows an increased share of negative flexibility.

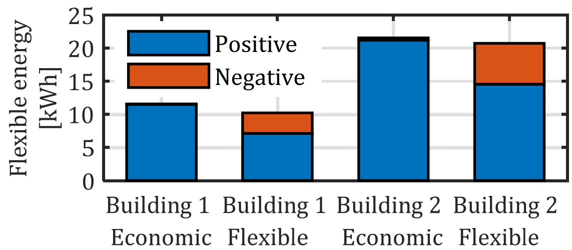

Fig. 4– Comparison of the yearly mean value for the 12 hours flexibility.

The results for the buildings are summarized in table 1. For both considered buildings, the economic controller shifts the loads to lower price regions, noticeable by the lower mean price. The heat pump's electrical demand for the flexibly operated buildings is 7 %, respectively 13 %, higher than for the economical operation. This leads to lower total operating costs. The mean load shifting capability of the flexibly operated buildings is increased, i.e. building 1 is able to reduce its load by 21.3 %. Both buildings show a flexibility factor of 0.3, whereas the factor is almost 0 for the economically controlled buildings.

5.2 Discussion

In the following section, the results are discussed briefly. The economic controller can shift loads to low price regions (figure 2). This happens through operating the heat pump at full load during local price minima and turning it off if possible. The indoor air temperature is kept close to the lower limit to avoid heat losses, this limits the available negative flexibility. In contrast, the proposed novel control approach greatly increases the available negative flexibility. Through a longer lasting low price the

Tab. 1 – Comparison of KPIs for the flexibly (Flex) and economically (Eco) controlled buildings. A bar indicates yearly mean values. The following KPIs are shown: Price ($\bar{\rho}$), electrical demand of heat pump ($E_{total,el}$), seasonal COP ($SCOP$), relative load shifting capability ($\bar{\varphi}^{-}_{rel,12h}$) and flexibility factor ($\overline{FF}$).

KPI	Unit	Building 1		Building 2	
		Eco	Flex	Eco	Flex
$\bar{\rho}$	$\frac{1}{kWh}$	0.37	0.39	0.40	0.42
$E_{total,el}$	$\frac{kWh}{m^2 \cdot a}$	18.6	21.0	40.5	43.2
$SCOP$	-	2.12	2.26	2.30	2.45
$\bar{\varphi}^{-}_{rel,12h}$	%	0.4	21.3	1.1	18.6
$\overline{FF}$	–	0.0	0.3	0.0	0.3

building is heated up, being able to perform load reduction for a longer duration.

As the load of a single building is too low to participate in the electricity market, buildings need to be aggregated. Aggregating flexibly controlled buildings, unlike cost optimally controlled buildings, yields several advantages from the grid's point of view. As the load smoothly follows the price signal, a load forecast can be performed more easily. Additionally, the proposed flexible controller only uses the current price as a control signal. This allows short term price increases while the flexibly controlled building can lower its load. These aspects are essential for a cost-effective operation of the grid, as deviations from the planned consumption can be balanced more easily.

Providing negative flexibility leads to higher electricity demand, as the indoor air temperature needs to be elevated. Thus, future electricity contracts should include a refund to increase the building operator's willingness to provide flexibility. Today's electricity tariffs are flat in many European countries. Building operators might agree to control their heat pumps flexibly and not cost optimally if they are offered a variable price, that is lower than the flat one.

6. Summary and conclusion

The growing share of renewables and the electrification of the heating sector increase the need for consumer flexibility. Due to the thermal capacity of buildings, heat pumps are suitable for flexible operation. Flexibility is the ability to change the demand following a price signal. Consequently, the cost-optimal formulation of Model Predictive Control (MPC) is the mainly used approach to exploit the building's energy flexibility. This work presents a new control algorithm, which aims to increase the building's energy flexibility. First, the available flexibility is determined through solving two optimal control problems. Next, the control input is calculated according to a price signal. A case study is conducted and the operation of an economic and a novel flexible controller are compared on a yearly basis. The economic controller usually keeps the building's temperature at the lower limit of the comfort band. The available negative flexibility is close to zero, as the possibility to decrease the load is prevented. In contrast, the flexible controller provides 30 % of the total flexibility as negative flexibility. This corresponds to the possibility to reduce the mean demand by around 20 % of the nominal load. Additionally, the new flexible controller shows a smoother load that follows the price signal. These characteristics qualify the flexible control approach for aggregation of buildings. The flexible operation is achieved through an elevated temperature. This goes along with increased consumption of around 7…13 %. As the electricity tariffs are flat in most European countries, the introduction of variable prices is a promising incentive for building operators to control their heat pumps flexibly.

7. Acknowledgement

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8. Appendix A

The parameters (table 2) used for the simulative model are adapted from [4]. The heat transfer coefficient R_{hi} for Building 2 was adjusted to meet design values in [27]. The window area A_w is an effective value including the transparent area and transmittance. The heated living area is denoted by A_h.

Tab. 2 – Model parameters.

Parameter	Unit	Building 1	Building 2
A_h	m^2	111	160
A_w	m^2	2.34	2.94
C_i	kJ/K	$5.11 \cdot 10^3$	$9.94 \cdot 10^3$
C_e	kJ/K	$4.15 \cdot 10^4$	$4.51 \cdot 10^4$
C_h	kJ/K	-	$9 \cdot 10^3$
C_s	kJ/K	$2.01 \cdot 10^3$	$2.01 \cdot 10^3$
R_{ea}	K/kW	15.73	10.28
R_{hi}	K/kW	-	1.0
R_{ia}	K/kW	34.48	7.12
R_{ie}	K/kW	1.04	0.46
$P_{el,max}$	kW	1.21	2.76

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