Potential impact of energy cost optimization for electrical floor heating systems under day ahead spot electricity prices and user set comfort levels

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Abstract: In this article the potential of cost optimization for electrical floor heating systems is studied. Model Predictive Control (MPC) based optimization method is used to optimize energy costs of electric floor heating while taking into account user set temperature restrictions (comfort levels) and dynamic day ahead electricity spot prices. The aim of this paper is to find what effect does MPC optimization have to the expenditure costs of direct electric floor heating systems. MPC is optimized according to the dynamic electricity prices and user temperature restrictions. This means that optimization problem is solved by taking into account hourly electricity price fluctuations which can mean that power consumption is shifted off from peak price hours to low price hours while taking into account all the restrictions, including user comfort. Data collected from different heating systems is used to run simulations for heating scenarios, including base scenario and several optimized scenarios. Data sets from quarter one 2016 to quarter two 2017 are used for the simulations. The obtained results are compared and total cost savings in a year are calculated.

Key–Words: Electric floor heating expenditure cost optimization; Day ahead electricity spot prices;

1 Introduction

The increase in intermittent renewable electricity production and liberalizing electricity markets are creating many opportunities and challenges for electricity consumers, producers and system operators. The more renewable energy production units, such and wind turbines and solar panels, are integrated into power grids, the more volatile energy markets can become. It is not uncommon for the electricity price to fluctuate more than 2000% within a single day on energy markets such as Nord Pool Spot. This creates challenges for electricity producers and transmission system operators as described in [1]. Electricity consumers however, can benefit from these fluctuations [2].

To face these growing challenges, smart energy grid technologies have been seen as one of the best solutions. The concept of smart grids and demand response have been introduced several years ago in various literature such as [3].

Thanks to the wide dispersal of smart meters, electric utility companies are able to sell electricity with spot prices to the consumers in the Nord Pool Sport electricity market area. This means that consumers will be charged for how much they consumed in an individual hour and what was the electricity price in the spot market for that hour. As the spot markets are volatile, this creates opportunities for electricity consumers to reduce their costs by consuming more energy during the cheaper time periods and cut their consumption during the expensive hours.

This type of demand side response to energy markets has been studied in various researches. The authors in [4] have concluded that compared to traditional operations of heat pumps with constant electricity prices, the optimized operating strategy saves 25-35% of the electricity cost. Authors in [5] have researched partial storage electrical heating systems and have concluded that with optimal demand response control, a partial (40% from required daily heat) storage heating system can achieve as high as 46% energy cost savings.

In this article, the effects of MPC optimization on the electricity cost of electrical floor heaters are studied. The aim is to find how much could electricity consumers with electrical floor heater save yearly if volatile energy prices are taken into account in the heating processes. This subject is specially interesting for Northern countries, where a lot of radiant electric floor heating is being used. For example, in Estonia, which is one of the smallest economies in Europe, about 15% of households have one ore more electric floor heaters installed [6]. With an average electrical power of 0.7kW per floor heater, this makes minimum of 60MW of electrical power in Estonia that has a potential for cost optimization.

The optimization effect is studied under various circumstances and with different simulations. Simulations are ran both for a single heating season (quarter one of 2017) and for a whole year (2016).This distinction is made for two key reasons - to show the effect of seasons and because data from test floor heaters was available only from Q1 2017 (for the whole year of 2016, the same heater characteristics are used as for 2017). Simulations are as followed:

- Simulation 1 and 2 are base scenarios for heating season (2017 Q1) and for the whole year (2016). In the base scenario the floor temperature is kept constantly at 23 degrees through out the period (no cost optimization is added).

- Simulation 3 and 4 are MPC optimization scenarios for heating season and for the whole year, where comfort level for the user is kept the same but maximum savings are strived for.

- Simulation 5 is MPC optimization scenario for 2016 where minimum temperature is kept constantly at 23 degrees.

- Simulation 6 studies lowering or rising the temperature restrictions and its effect on electricity cost in the case of the heating season.

- Simulation 7 is MPC optimization scenario for 2016 where minimum temperature is lowered by 3 degrees.

Comparing these scenarios, preliminary conclusions can be made.

To calculate the effect of MPC optimization, the following data has been used:

- The average characteristics of 5 electrical floor heaters that were monitored over a test period of 01.01.2017 – 31.03.2017. All the heaters were used in bathrooms from range of $5m^2$ – $9m^2$.

- Energy consumption of a floor heater from 01.01.2017 to 01.02.2017.

- NPS Estonian region electricity prices from 01.01.2016 to 31.03.2017 [7].

- Electricity transmission costs based on the price-list of electricity transmission company [8].

- VAT tax of Estonia (20%)

This paper has been divided into five sections. Section II gives an overview of the topic and what are the necessary prerequisites to calculate savings, section III shows the MPC optimization method, section IV presents the calculations, simulations and the results and section V concludes the paper.

2 Overview of the topic. Prerequisites to calculate optimization effects.

To provide heat and comfort in residential buildings, radiant floor heating systems are wildly used. Among these systems, one of the most simple method is using direct electric heating cables, which are placed into the structure of the floor, like concrete. When powered on, these cables start to heat the floor.

When lowering the cost of energy for electric heating, it can be done by changing 2 variables - amount of energy used (kWh) and the time it was used (h). Lowering the quantity of electricity consumed (kWh) is almost universally accepted method of reducing the cost of heating as electricity is usually charged for the amount that is consumed (€/kWh). For this purpose, power meters are installed to consumers. In recent years and in certain markets, the time of electricity consumption has become as important for the total cost of heating. This is due to the fact that numeral electric utilities sell electricity with different rates during different times. In some countries in Europe, utilities also sell electricity with spot price based packages to their clients, meaning customers have different price in every hour. Thanks to the smart meters installed, utility companies are capable of also tracking how much electricity is being consumed in every hour by individual clients and thus charge them accordingly. This also gives the possibility for electricity consumer to reduce their costs by shifting the energy consumption to lower priced hours [9].

Due to the large heat capacity of most floors, electric floor heating is well suited to be optimized by shifting the electricity consumption. This means that when the energy price is low, the floor can be heated with maximum power and usually heat for several hours can be stored into the floor material. When the heating is turned off, the floor will cool down based on its cooling characteristic and how much heat was pre stored in the floor.

In this paper, MPC optimization method is used to reduce the cost of electric floor heating by lowering the amount of electricity consumed and by shifting the energy consumption to the optimal time frames. As authors in [10] have shown, one of the key restrictions to be used in these types of optimization challenges is customers comfort.

There are four heating scenarios simulated in this paper:

- **Base scenario.** In this scenario, electricity consumption of an electric floor heater is simulated by keeping the floor temperature at a constant 23 degrees through out year 2016 and quarter one of 2017 (one heating season).

- **Comfort scenario.** In this scenario, electricity consumption is optimized by a MPC method while user comfort is kept. User comfort is defined as follows: maximum allowed floor temperature is 30 degrees and minimum allowed floor temperature is 20 degrees except for hours of 7-8 (CET) and 20-21 (CET), where the minimum temperature is 23 degrees. This corresponds to the user comfort as a predefined time windows for using ones bathroom. Simulation is made over a period of year 2016 and quarter one 2017 (one heating season).

- **Effect of spot price.** In this scenario, the effect of spot prices in the MPC optimization method is studied. For this, the minimum temperature is kept in constant 23 degrees and maximum allowed temperature is constant 30 degrees. Simulation is made over a period of year 2016.

- **Effects of temperature change.** In this scenario, the effect of lowering or rising the temperature by 1 degree is studied by simulating heating over the period of quarter one 2017. To study the effect on energy cost of floor heating, another scenario is simulated where over the year of 2016 the minimum floor temperature is lowered to 20 degrees and MPC optimization is used to achieve maximum savings.

To calculate the savings effects under the open market circumstances with the data from 01.01.2016 to 31.03.2017, the following prerequisites are needed to be found:

- The average electrical power needed to heat 1m^2 with floor heating (W/m^2)

- Ratio of ON and OFF state of electric floor heating ($t \cdot 100/24$)

- Average yearly electricity consumption of a floor heater (kWh)

- The saving percentage of MPC optimization method (%):

  - When reasonable comfort has been kept for the user

  - When temperature is lowered by 1°C

3 MPC optimization method.

3.1 Temperature model

Differential equation describing the change of the inside temperature (general and continuous case).

$$\frac{dT^i(t)}{dt} = \alpha(t)(T^i(t) - T^o(t)) + \kappa(P)P(t) \quad (1)$$

To calculate the parameters that are needed for optimization, we will create difference equation from equation (1) using the assumptions.

$$\frac{T^i_{t+\Delta t} - T^i_t}{\Delta t} = \alpha_t(T^i_t - T^o_t) + \kappa P_t \quad (2)$$

For simplification we will omit the time dependence of thermal diffusivity α_t:

$$\frac{T^i_{t+\Delta t} - T^i_t}{\Delta t} = \alpha(T^i_t - T^o_t) + \kappa P_t \quad (3)$$

Equation system (3) can be solved for α and κ with linear regression.

3.2 Optimization model for temperature control

In this section, the optimization model used to minimize the costs of heating is described. In this work, linear programming model is used to minimize the costs.

Sets (indices):

- t_L – level (temperature) time;
- t_P – power time;
- $t_{\mathbb{P}}$ – price time.

Parameters:

- $\delta_{\mathbb{P}P}$ – price to power time conversion matrix;
- δ_{LP} – level to power time conversion matrix;
- $\mathbb{P}_{t_{\mathbb{P}}}$ – total price per consumed power;
- T^{start} – temperature at start;
- α_{t_P} – thermal diffusivity;
- κ – heat generation per unit power;
- $P^{\min}_{t_P}$ and $P^{\max}_{t_P}$ – minimum and maximum power;
- $T^{\max}_{t_P}$ and $T^{\min}_{t_P}$ – minimum and maximum temperature;
- $T^o_{t_L}$ – temperature outside of the reservoir.

Variables:

- $P_{t_P} \in \mathbb{R}^+$ – power;
- $T^i_{t_L} \in \mathbb{R}$ – temperature inside the reservoir (measured temperature);
- $\Delta T^{\min}_{t_L} \in \mathbb{R}^+$ – degrees under minimum temperature;
- $\Delta T^{\max}_{t_L} \in \mathbb{R}^+$ – degrees over maximum temperature.

Objective function to be minimized:

$$C = \sum_{t_{\mathbb{P}}} \left[\mathbb{P}_{t_{\mathbb{P}}} \left(\sum_{t_P} P_{t_P} \delta_{\mathbb{P}P} \right) + \sum_{t_L} \left(\mathbb{P}^{Pen} \delta_{\mathbb{P}P} \left(\Delta T^{\min}_{t_P} + \Delta T^{\max}_{t_P} \right) \right) \right] \quad (4)$$

Physics constraint (generalization of equation (3)):

$$\frac{T^i_{t_L+1} - T^i_{t_L}}{\Delta t_{t_L}} = \alpha \left(T^i_{t_L} - \sum_P T^o_{t_P} \frac{\delta_{LP}}{\delta_{LP}} \right) + \sum_P \kappa P_{t_P} \delta_{LP} \quad \forall t_L \quad (5)$$

Power constraint:

$$P^{\min}_{t_P} \le P_{t_P} \le P^{\max}_{t_P} \quad \forall t_P \quad (6)$$

Penalty constraints:

$$\Delta T^{\min}_{t_P} \ge T^{\min}_{t_P} - \sum_P \delta_{LP} T_{t_L} \quad \forall t_P \quad (7)$$

$$\Delta T^{\max}_{t_P} \ge \sum_P \delta_{LP} T_{t_L} - T^{\max}_{t_P} \quad \forall t_P \quad (8)$$

Start boundary condition:

$$T_0 = T^{start} \quad (9)$$

The result of MPC optimization are dependent of several factors, like:

- price fluctuations;
- temperature fluctuations outside of the heated room (erg reservoir), this also includes other heat sources in the house;

- thermal diffusivity, which in turn is dependent of:
  - human behavior;
  - insulation of the house;
- Heat capacity of the heat source.

4 Calculations, Simulations and Results

4.1 Thermal characteristics

The thermal characteristics described in equations (3) and (5) were obtained by measuring the temperature and power of 5 devices. Characteristics were obtained by linear regression of equation system (3). The results are displayed in table 1.

Table 1: Characteristics obtained by measurements

Characteristic	Value
α	0.0145
κ	1000

4.2 The average electrical power needed to heat 1m^2 of floor space

The average power needed to heat 1m^2 of floor can be derived from industries practice. Table 2 shows the values of recommended power for electric floor heating. Lower values should be used only in well isolated buildings. This table also corresponds to the results shown in [11].

Table 2: Recommended power for electric floor heating installations [12]

Use area	Power (W/m^2)
Living space	70-90
Bathrooms	80-120
Cold storages	15-20

4.3 Ratio of ON and OFF state of electric floor heating

To calculate the working ratio of electric heater, data from a test heater in a bathroom is used. Test electric floor heater was kept on a constant temperature of 25 degrees, which corresponded to the comfort level of that user. Results of the test:

- Period monitored: 01.01.2017 - 01.02.2017
- Maximum power of the heater: 860W
- Electricity consumed in the test period: 203.1kWh.

The ON and OFF state ratio can be calculated as $203.1 \cdot 100/(0.86 \cdot 24 \cdot 32) = 30.7\%$

The heater was in ON state for 30.7% of the test period.

Due be noted that the ON OFF ratio is highly dependent on the desired temperature of the heated floor. The ratio can fluctuate from 0% (heating is always off) to 100% (heating is always on). This use case shows, for example, a real user keeping his floor in his desired temperature range.

Following the conclusions in subsection A and B, it can be calculated that a 7m^2 bathroom can consume $700W \cdot 24 \cdot 365.25 \cdot 0.307 = 1884kWh$ in a year.

4.4 The saving percentage of MPC optimization

4.4.1 Introduction of optimization calculations

To find the savings percentage of MPC optimization technology, data of year 2016 and Q1 of 2017 is used. The average cooling and heating characteristics of 5 electric floor heaters are used to simulate four scenarios:

- Keeping constant temperature of 23°C in year 2016 and Q1 2017.
- Comfort scenario: MPC optimization with comfort temperature in 2016 and Q1 2017.
- The effect of spot prices in MPC optimization method (in year 2016)
- Temperature lowering: the effect of lowering temperature by 1-3°C

To calculate the savings percentage of the MPC optimization, simulations on 2016 and 2017 Q1 data are made.

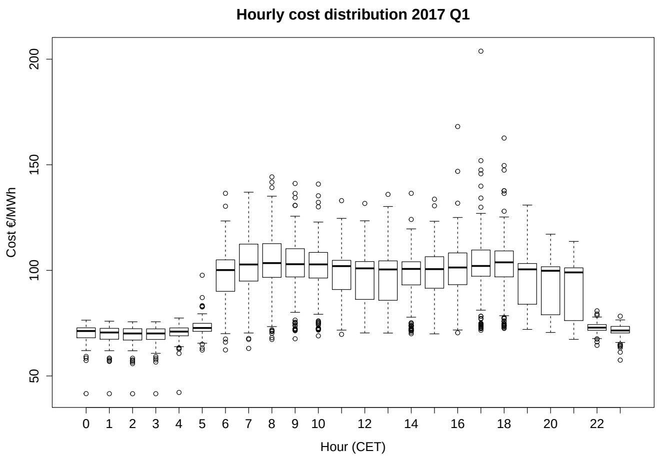

Figure 1: Distributions of hourly cost of electricity (SPOT price, transmission costs and VAT) in Q1 2017

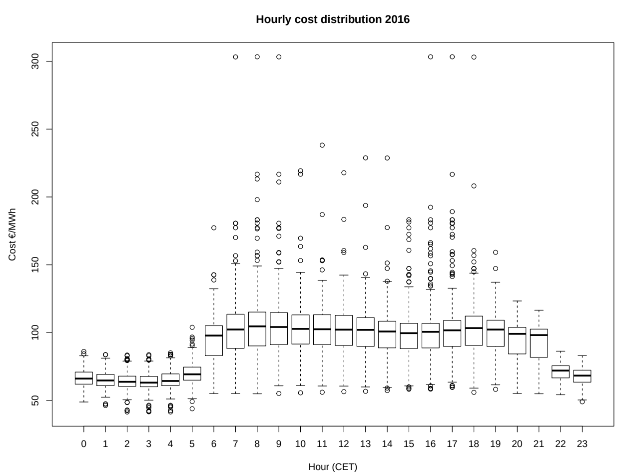

Figure 2: Distributions of hourly cost of electricity (SPOT price, transmission costs and VAT) in 2016

Figure 1 shows the distribution of hourly cost in Q1 2017 and figure 2 shows it in 2016.

Following estimations are made with simulations:

- minimum temperature is 20°C;
- maximum temperature is 30°C;
- temperature at the start of each day is 23°C;
- maximum power of the heater is 1.0kW;
- Outside temperature for Q1 2017 is taken as 1°C (2017 Q1 average). Outside temperature for 2016 is taken with hourly intervals of what the temperature was in Tallinn Estonia according to the database of Weather Underground [13].

4.4.2 Base scenario of 23°C

In the base scenario, constant temperature of 23°C is kept for the heating season (Q1 2017) and for the whole year period (2016). The distribution of daily costs with 23°C held constantly in 2017 are shown in figure 3 and in 2016 on figure 4 as a boxplot.

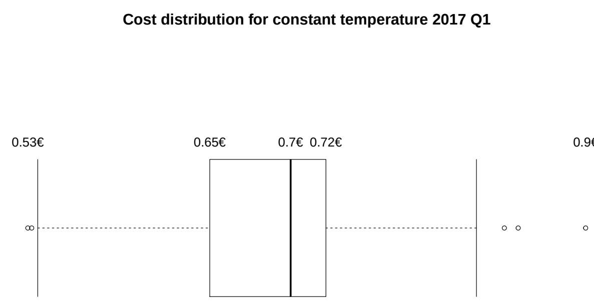

Figure 3: Distribution of simulation runs with 23°C held constantly in Q1 2017

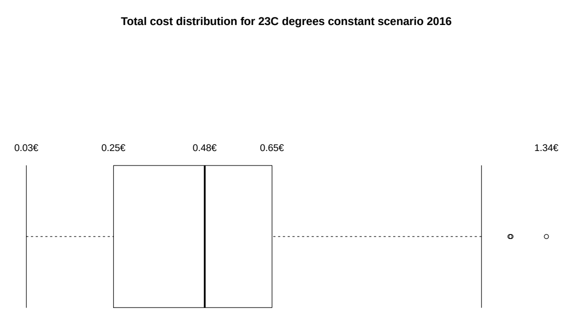

Figure 4: Distribution of simulation runs with 23°C held constantly in 2016

The results of the simulation shows that in Q1 2017 the heater would have consumed electricity with the average cost of 0.68€/day and in 2016

0.48€/day. The average consumption of electricity in Q1 2017 is 0.67MWh and in 2016 1.98MWh.

4.4.3 Simulation with customer comfort

A prerequisite is that comfort is held for the customer if minimum temperature is held 23°C for hours 7-8 (CET) and 20-21 (CET) and 20°C is held for all other hours.

When comparing these results with the base scenario of 23°C we get the distribution for savings, which is visualized on figure 5 and figure 6 as a boxplot.

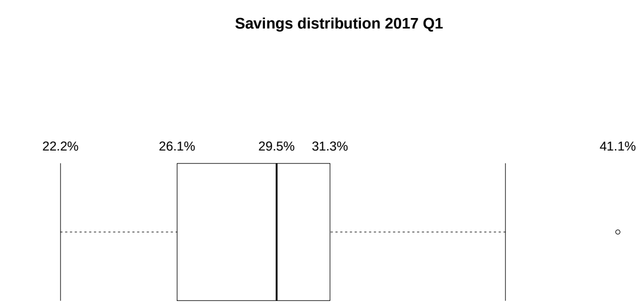

Figure 5: Distributions of daily savings from optimization in Q1 2017.

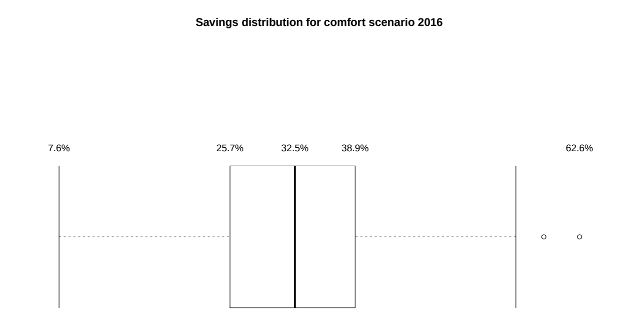

Figure 6: Distributions of daily savings from optimization in 2016.

This shows that by optimizing the customers' heating, it is possible to save on average 29.5% (Q1 2017) and 32.5% (2016) of the heating cost while keeping the minimum required comfort. Throughout the simulation period of Q1 2017 the minimum savings effect achieved on a single day was 22.2% and maximum 41.1%. Throughout the simulation period of 2016 the minimum savings effect achieved on a single day was 7.6% and maximum 62.6%.

Figure 7 shows the daily cost distribution in 2016 with the comfort scenario. During the summer months a lot less heat is needed and thus the costs are down.

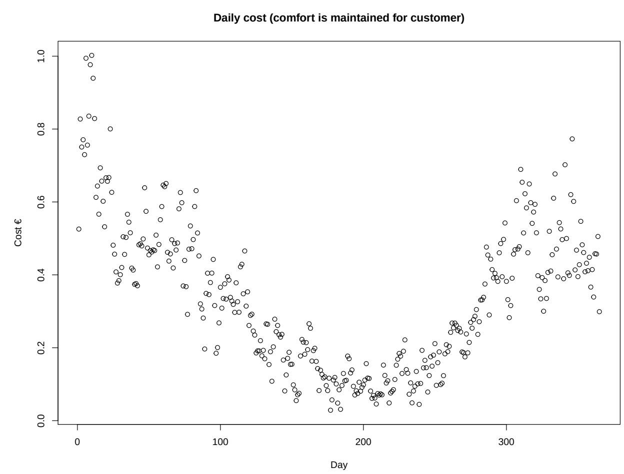

Figure 7: Distributions of daily costs with optimization in 2016.

4.4.4 The effect of spot prices in MPC method

To study the effects of spot price in previous cost optimization, a MPC optimization simulation is ran with minimum temperature constantly at 23 degrees and maximum temperature constantly at 30 degrees. In this scenario, the cost savings are achieved only through sifting the time that electricity is consumed and not by also lowering the medium temperature. The simulation is made with data from year 2016 and when compared with the base scenario, we get the distribution for savings which is visualized on 8 as a boxplot

This shows that without lowering the minimum temperature, it is possible to save on average 16.8% from electric floor heating energy costs just by optimizing electricity consumption against day ahead electricity prices. Throughout the simulation period of 2016 the minimum savings effect

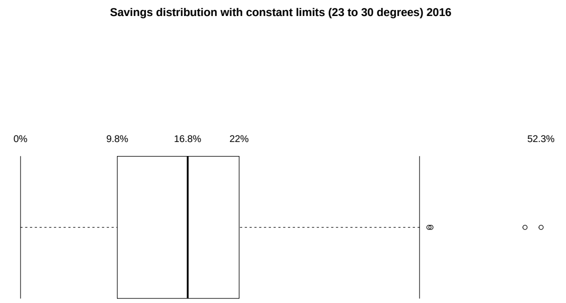

Figure 8: Distributions of daily savings from only spot price based optimization in 2016.

achieved was 0% and maximum effect was 52.3%.

4.4.5 Effects of temperature change

To study the effects of changing the temperature restrictions of floor heaters, simulations are made to:

- lower the constant temperature held by a degree
- use MPC cost optimization while lowering the minimum temperature of the floor to 20 degrees and raising the maximum temperature to 30 degrees.

The simulation of reducing the constant temperature held by a floor heater (in Q1 2017) by 1°C reduces the overall cost of electricity by 4.5%. This effect of course is also dependent on the starting temperature as heating and cooling characteristics of floors are exponential.

In figure 9 it shows that when using MPC cost optimization and lowering the minimum temperature to 20°C, it is possible to achieve on average 75.5% cost savings in a year (2016). The minimum savings achieved were 29.4% and the maximum savings reached up to 100%. This is due to the fact that during summer months, on certain days no heat is required to maintain the temperature of the floor above 20°C.

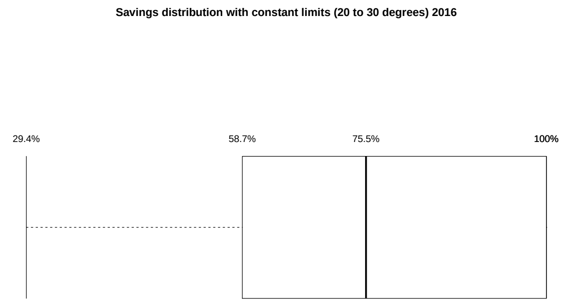

Figure 9: Distributions of daily savings by lowering minimum temperature to 20°C and using cost optimization in 2016.

5 Results and conclusions

The aim of this paper was to study the potential cost savings of MPC optimization for electric floor heaters under open electricity markets by using experimental analysis. For this purpose, different scenarios where simulated with the data obtained from 5 electric floor heaters over the time period of quarter 1 2017. With this data, 4 simulations were run:

- Base scenario of keeping the floor temperature on constant 23°C.
- Comfort scenario where MPC optimization was used to reduce costs.
- The spot price effect on optimization scenario.
- The temperature change effect on optimization scenario.

From these simulations, following results and conclusions can be made:

- Compared to maintaining the same constant floor temperature of 23°C, the proposed MPC cost optimization method is capable of lowering the electricity cost of a electric floor heating system on average:
  - 29.5% under the data set of the Q1 2017 heating season.

  - 32.5% under the data set of one year (2016).

  To be noted, that in the optimization problem, user comfort was taken into account and the comfort level was kept the same for the user.

- From the data set of year 2016, it is shown that the effect of spot prices in MPC based optimization method can account for 16.8% of the total cost savings for the end user.

- Based on the data of Q1 2017, it is shown that costs savings of 4.5% can be achieved when lowering the minimum temperature by 1°C. Furthermore, based on the data of 2016, it is possible to save 75.5% from the electricity cost (compared to maintaining constant 23 degrees) when lowering the minimum temperature from 23°C to 20°C and using proposed MPC optimization method.

To calculate the potential savings of a electric floor heater using MPC based optimization method under open electricity market conditions, some prerequisites can be made. As shown and calculated in this paper, following results can be used for such calculations:

- Average power of floor heaters used in bathrooms per m^2: $100W/m^2$

- Ratio of ON and OFF state in normal heating conditions: 25%-35% (dependent on the temperature of the floor).

- the potential of MPC optimization method 16%-35% (dependent on the conditions and restrictions).

In the current works a rather small amount of test objects was used to find the energy savings. Therefore, in future works more test objects should be used to determine the effect of MPC optimization in different situations. Also, in further research different electricity markets should be compared and besides day ahead spot prices, other electricity market financial opportunities should be considered. Such opportunities could be intra day electricity prices on frequency markets. For third, the environmental effect of large scale MPC optimization on electric floor heaters should be studied.

The cost optimization proposed in this article is not only for electrical floor heaters, but it can easily be expanded to other electricity consumers with intermittent storage capabilities. These can be other electrical heating systems, such as heat pumps or water boilers, storage heaters and etc. It can also be used in cooling systems such as Air Conditioners or industrial cold storages. Therefore, this type of MPC optimization method can be an effective method in generally reducing the costs involved in electricity consumption and production.

Acknowledgements

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