Action 8

Development and assessment of a technical solution for an improved management of the grid in the GR

Final Report

Part of the project:
Power to Heat for the Greater Region's Renewables Integration and Development - PtH4GR2ID
Project number : 031-4-09-004

GECT- Autorité de Gestion Programme Interreg VA Grande Région, Secrétariat Conjoint, 11, bd. J.F. Kennedy, L-4170 Esch-sur-Alzette

Contractor:

Université de Liège

Building Energy Monitoring and Simulation

Professor Philippe André

Place du XX Août, 7

B-4000 Liège

Tel: +32 (0)63 23 08 58

e-Mail : p.andre@ulg.ac.be

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Responsible partner: TU/GST

Participating partners:

- TUK/ESEM
- IZES
- ULiège/BEMS

2. Objectives of the action

1. Conception of a model-predictive controller for HPs
2. Integration of heat pump, storage system, building model and controller in a single simulation model
3. Simulation based assessment of energy efficiency under different scenarios

3. Motivation PtH4GR²ID

An increasing share of renewable energies (RE) is essential to fulfil the climate targets of individual countries and the European Union (EU). However, the RE that are mainly generated by solar radiation and wind in the Greater Region (GR) do not only offer advantages over conventional power plants. The main problem is the fluctuation in these energy sources. While power generation from coal, gas or nuclear power plants is relatively well adapted to demand, generation from renewables depends on the energy source. This presents major challenges for the electricity grid in particular, as supply and demand must always balance each other out.

The most common solution currently being investigated in research and used in practice are electric storage systems as batteries. With such systems it is easily possible to balance the time difference between generation and demand. However, the implemented solutions are often costly, do not have very good efficiency or are not sustainable. Therefore, an increasing focus should also be placed on adapting the demand more towards the generation - this is commonly known as Demand Side Management (DSM). A requirement for DSM is that “shiftable” loads can be determined. Basic loads that have to be covered around the clock are negligible. However, there is an interesting potential for heat generation in buildings in particular, since almost every building has a heat storage. The generation of heat must therefore not necessarily be based on the current heat demand, but can also be controlled considering external factors.

This is one of the focal points in the PtH4GR²ID project. One of its goals is to design a model-predictive control system (MPC) for heat pumps (HP) that can shift the operation time of the HP to times when the electricity grid needs to be relieved. Heat pumps belong to the category of power-to-heat systems - this generally describes the process of using electricity to generate heat. Due to the increasing share of renewables in the electricity mix and the good effectiveness of heat pumps, they have become an increasingly used technology, especially in new buildings. If, in the future, a high proportion of renewables in the grid will lead to lower prices in order to provide an attractive incentive for consumers, an appropriate control system will not only help to relieve the electricity grid, but will also lead to financial savings for the end consumer.

Such a control system, which includes a simplified building model, accesses predictive weather data and additionally receives a signal from the electricity grid, will be developed within the project, tested at simulation level and then subjected to trials in a climate laboratory. The following report on Action 8 deals with the development of the controller (Action 8.1), the establishment of a simulation environment (Action 8.2) and the results of the simulation (Action 8.3).

4. Approach

4.1. Development of the Controller

In this project, we focus on a MPC for air/water HPs with a variable frequency that uses a simplified building model and an electricity tariff as inputs, predicts the weather and generates an operation plan for a time horizon of 48 hours. With the weather prediction and the building model, the controller can estimate the heating demand of the SFHs. By comparing this demand with the stored heating capacity in the water tank, the power consumption of the HP can be shifted to the most economic periods. These periods can be described as the ones with the “best” grid signal and the highest coefficient of performance (COP). If the grid input is an electricity price, the best signal refers to the cheapest periods. If it is a direct grid signal, it refers to grid-friendly periods with a high share of renewables. In the project, we use a direct price signal as an input.

This MPC-approach results in a higher efficiency and lower electricity costs for consumers. For further information about the used controller, a more detailed description can be found in [1].

4.2. Grid Signal

As mentioned in the previous section, the controller needs a grid signal. We use electricity tariffs as the grid signal so that the controller can directly detect periods with low prices to shift the operation time of the heat pump. For the modelling of these electricity prices, flexible tariffs were developed for each country in the GR. These tariffs, and the flexibility assigned to them, are based on actual prices on the day-ahead stock market in 2016. A detailed description of the prices and their modelling can be found in the detailed report to Action 7 or in [2].

Such flexible electricity tariffs for household customers, which can vary every quarter of an hour and which are based on short-term trading on the electricity exchange do not currently exist in any of the GR countries. Typically, in these countries nearly constant "heat pump tariffs" are available instead. This heat pump tariffs are cheaper than standard household tariffs but also allow the providers to switch off the heat pumps for a few hours per day. Accordingly, consumers can benefit from lower prices whereas providers can reduce the loads in peak hours. However, with an increasing share of RE in the grid, this approach will not be sufficient in the future and the general structure of the electricity market may change. The range of the assigned tariffs for each country is presented through boxplots in Figure 2.

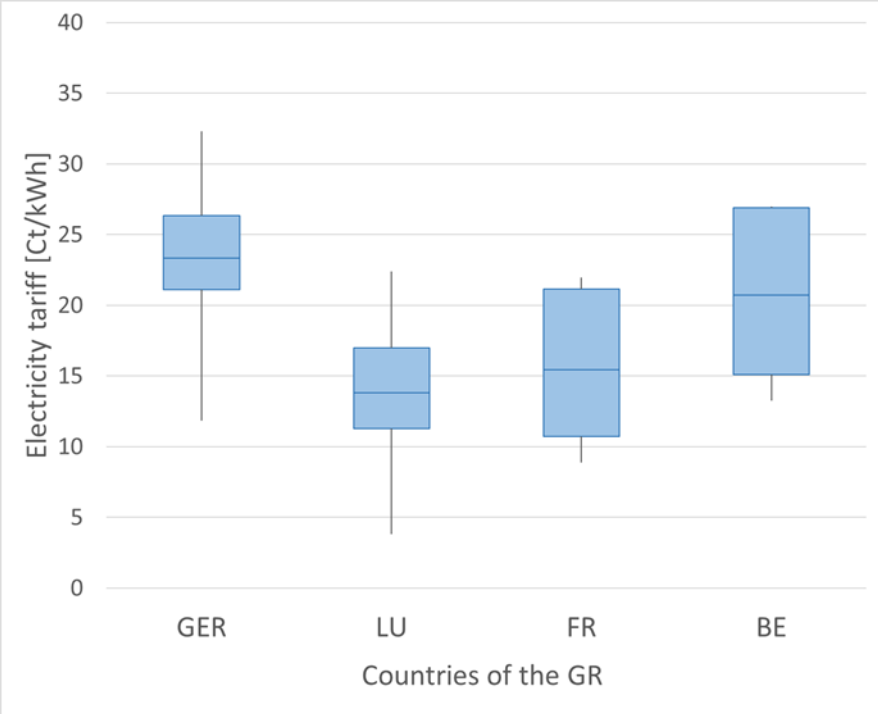

Figure 1: Structure of the electricity tariffs for every country of the GR

The boxplots were used to demonstrate the importance of the price fluctuation in addition to the maximum and minimum values. The boxes in the figure show 90% of all values as well as the median (the dash inside of the box). The whiskers outside show the distribution of the 10% left with the maximum and minimum prices.

The influence of this structure on the results and the functionality of the controller is discussed in section 5.

4.3. Development of a simulation environment

Work package 8.2 focuses on the development of an interface for the integration of the different simulation models. Within the project, models of reference buildings (Action 4; according to: [3]), the heat pump (Action 5.2), the storage system (Action 6), the electricity prices (action 7) and the controller (Action 8.1) were created. At the beginning of the project, it was decided to develop the models of the heat pump and the controller in MATLAB, which are mainly based on thermodynamic and mathematical principles. [4] The thermal simulations of the building and the storage system can be analysed in TRNSYS [5]. One of the challenges of this Action was to create an interface between the two simulation environments, which allows the exchange of variables during the simulation.

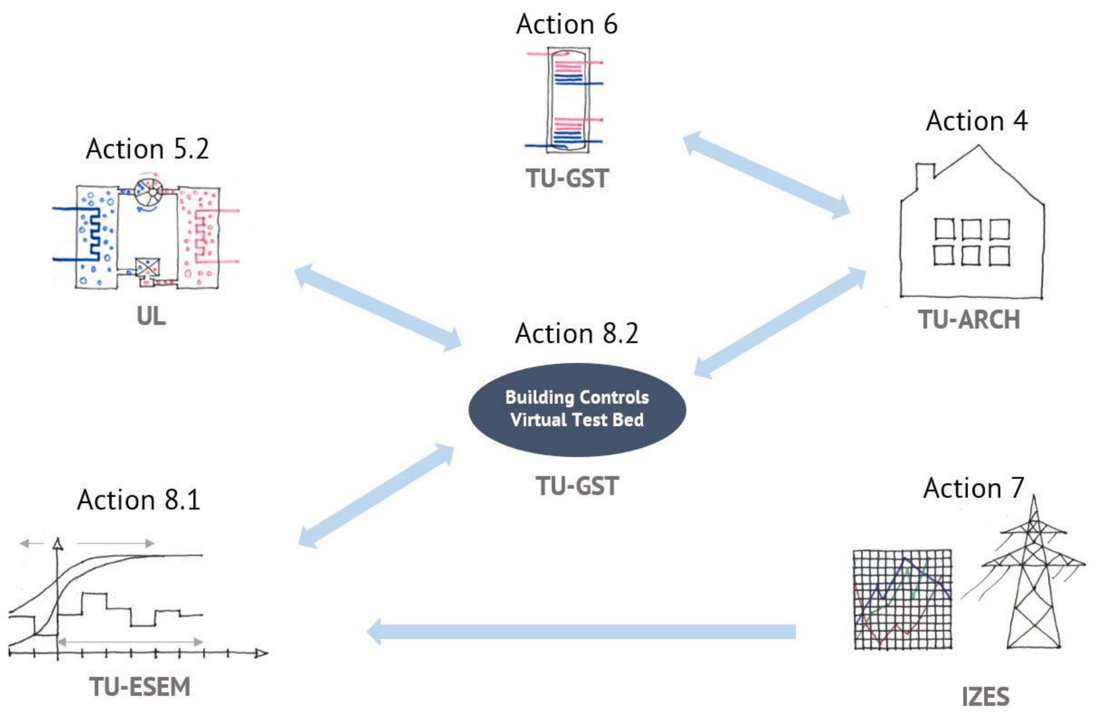

Figure 2: Simulation models and the corresponding Actions within the project

After research, the platform "Building Controls Virtual Test Bed" (short: BCVTB, (authors: [6]) was chosen, which is basically suitable for linking many different simulation programs and whose functionality is based on exchanging variables between different programs at fixed time steps. In the case of the project, this functionality is very well suited, since both programs can run independently and the communication between the programs (which is carried out by the BCVTB platform) is based purely on the exchange of variables. Figure 2 illustrates the structure of the simulation environment.

In Figure 3, two simulators are shown, each of them responsible for the execution of one of the used programs. Within the project, one simulator is executing TRNSYS and one MATLAB accordingly. Between the two programs, variables are exchanged as vectors at each time step, which can contain any number of elements. For illustrative purposes and to simplify error analysis, the vectors can be broken down into their individual elements using the "VectorDissassembler", allowing individual values to be analysed during the simulation. Afterwards the vectors can be merged again, the number of the individual lines clarifies thus also how many elements are exchanged at each time step between the programs. Furthermore, the boundary conditions must be defined before the simulation starts - the start and end times of the simulation as well as the time step are decisive here. In the selected simulation environment, these variables are defined as parameters because they remain constant during the simulation ("timeStep", "beginTime", "endTime"). The displayed values are represented in seconds and define the simulation for one year, with a time step of 15 minutes, since the controller is designed to transmit a signal to the heat pump every 15 minutes. These parameters are an input into the Actor "Boundary Conditions" and thus control the simulation process.

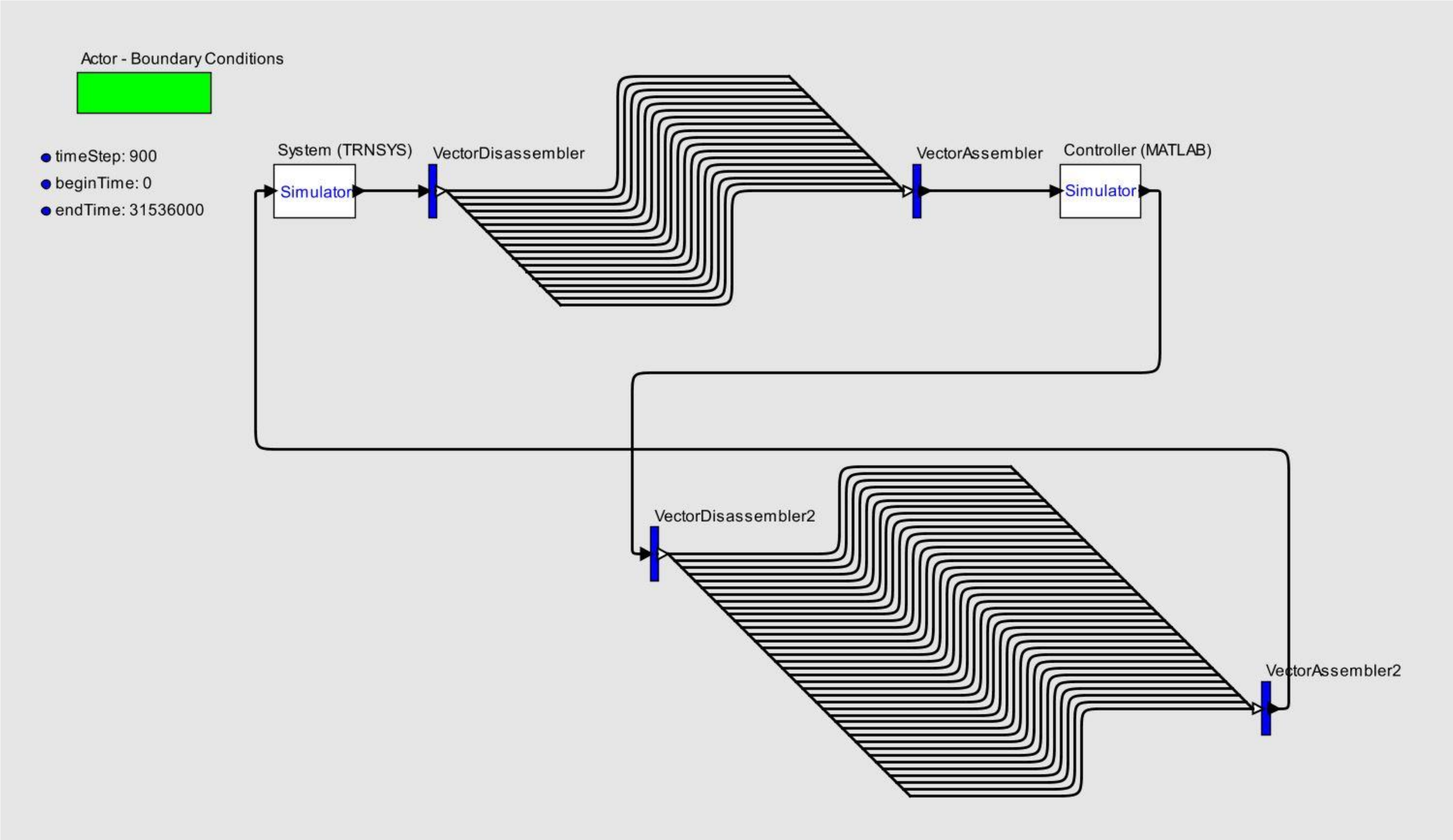

Figure 3: BCVTB - Simulation environment to couple MATLAB and TRNSYS

Another advantage of using BCVTB is that the linked programs can have their own time steps and do not have to be in line with the time step in BCVTB. This simplifies the simulations in TRNSYS. In TRNSYS, a time step of 15 minutes would be quite large in order to calculate the thermal behaviour of the different models with sufficient accuracy. Accordingly, TRNSYS can carry out any number of its own calculation steps although the variables are exchanged only every 15 minutes.

The functionality of the platform could be proven and empirical values for the exchange of variables could be collected by many different and simplified preliminary investigations. The figure shows the final version for linking all simulation models and therefore contains many vector elements which are exchanged at each time step. The choice of the platform has proven to be a good fit for the work within the project and especially within work package 8 and will also be applied to future projects in the field.

4.4. Simulation models TRNSYS

The thermal models needed within the project are developed in TRNSYS. In the following, the individual models are explained and the selection of the corresponding types in TRNSYS is explained.

- Building → Type56

For each country in the Greater Region, a reference building model was developed within the project. The selection and the modelling were carried out in Action 4. The models represent 3D-buildings created with Google Sketchup [7] software. Google Sketchup includes an interface to TRNSYS (TRNSYS3d), which makes it possible to import the buildings with all necessary information directly into the simulation environment. For this, TRNSYS uses the Type56, which contains all data of the examined models.

- Storage system → Type340 (Water) or Type840 (PCM)

The modelling of the storage system was carried out in Action 6 and can be read in detail in the corresponding report. Type340 was chosen for a pure water tank. Type840 has almost identical parameters, but also offers the possibility of integrating PCM into the storage. All storage systems were modelled in six different volumes (300 l – 2000 l), differences occur primarily in the thermal insulation.

- Heat distribution system → Type362 (Radiator) or Type653 (Floor heating)

Two different types were also selected to model the heat distribution system - radiators, which are still the most widely used system in the existing buildings of the GR. Surface heating systems should also be specifically investigated, as they are used in new buildings and lead to higher efficiency, especially in combination with a heat pump. However, radiators can also be used effectively with heat pumps. By refurbishing the thermal shell of a building, existing radiators are automatically oversized, especially in old buildings. This results in the advantage that lower supply temperatures are sufficient, which is very beneficial for the operation of the heat pump. The lower the difference between source and sink temperatures, the higher the efficiency of the HP.

Within the simulation environment, Types 362 and 653 were used for modelling. The power of the radiators and the radiant floor heating was adapted to the heating load of the corresponding building in accordance with the standard (DIN EN 12831, [8]). Additionally, there is also an internal possibility to model surface heating systems in Type56 ("Active Layer"), that was also carried out during the project.

- Thermostat regulator → Type320

A classic PID controller was used to control the indoor temperatures by adapting the mass flow of the heating system.

- Hydraulic control → Type11

The heat output of the storage tank and the extraction of domestic hot water (DHW) were modelled via various valves within the simulation environment. Especially since different thermal zones (usually two heated zones per building) are used within the building models, it is also necessary to model several heating circuits. The use of valves is necessary for this purpose and was solved in TRNSYS via Type11, which offers different possibilities to model valves.

- Weather files → Type15

TRNSYS also provides the user with various weather data that are available with the installation of the software. Thus it was possible to use a separate weather data file for each country of the GR, which contains reference data for the different locations based on historical weather data. Within the project, the locations Saarbrücken (for Germany), Nancy (for France), St. Hubert (for Belgium) and Trier (for Luxembourg) were chosen. As the database did not include weather data for Luxembourg, Trier was chosen as the location as it borders Luxembourg and shows sufficient accuracy to represent weather conditions. The corresponding data (temperatures, solar radiation, etc.) are read into TRNSYS via Type15.

- Soil temperature → Type77

The temperature of the ground does not play a decisive role in considering the heating needs of the buildings, but should still be considered within the project, as some buildings contain an unheated basement that is thermally linked to the ground.

- Domestic hot water demand → Type9

In contrast to the heating demand, the DHW demand is not defined by the building, but by the number of people living in the house. Within the project, a 4-person household was calculated and the DHW profiles were chosen accordingly. A corresponding profile was taken from the IEA Task 26 [9] and used for the simulations. It represents a classic hot water profile of a building with 4 inhabitants. This data sequence can be transferred to TRNSYS via a data reader. The energy for DHW is also mainly generated by the HP.

- Electric heating element → Type6

For the case that the heat generated by the heat pump is not sufficient for DHW-temperatures of at least 45°, an external electric heating element is available which can be used for post-heating. This is modelled in TRNSYS via Type6.

- Internal calculations → Equation-Type

For some variables it is necessary to do internal conversions or calculations. For example, the standard unit of power in TRNSYS is kJ/h, while the unit W or J/s is used in science. Such conversions could also be carried out afterwards during the evaluation of the results (within the project mostly in Excel), but the easiest solution is a direct conversion and subsequent output of the values in the relevant unit. For this purpose, TRNSYS provides so-called "equation-types", which allow simple mathematical calculations. Thus all energies and powers are transferred to the correct unit within the simulation.

- Internal Integration → Type24

When analysing the simulation results, there are a large number of different variables that are considered. For some of these variables (especially temperatures) it is necessary to consider the values for single time steps. However, for other results the sum at the end of the year is decisive, especially regarding energies. Analog to the internal calculations, this could be summed up manually when evaluating the results, but TRNSYS offers the possibility to use a type which automatically integrates the corresponding values and thus directly outputs the relevant results of the annual simulation.

- Output of the results → Type65

The last step of the simulation is the output of the results. These can be plotted in various formats, within the project all results are printed into a .txt file and then transferred to Excel. Accordingly, an online plotter (the course of the single outputs can be viewed during the simulation) with "Output-File" (Type65) was selected.

- Interface to BCVTB → Type6666

An important step in the simulation model is the possibility of exchanging variables between TRNSYS and MATLAB using the BCVTB platform. A separate type (Type6666) exists for this purpose, which represents the interface to MATLAB. In this type, only the number of variables exchanged per time step and the frequency of exchanges are defined. In the context of the project, 55 variables per time step are exchanged between TRNSYS and MATLAB, the exchange takes place every 15 minutes.

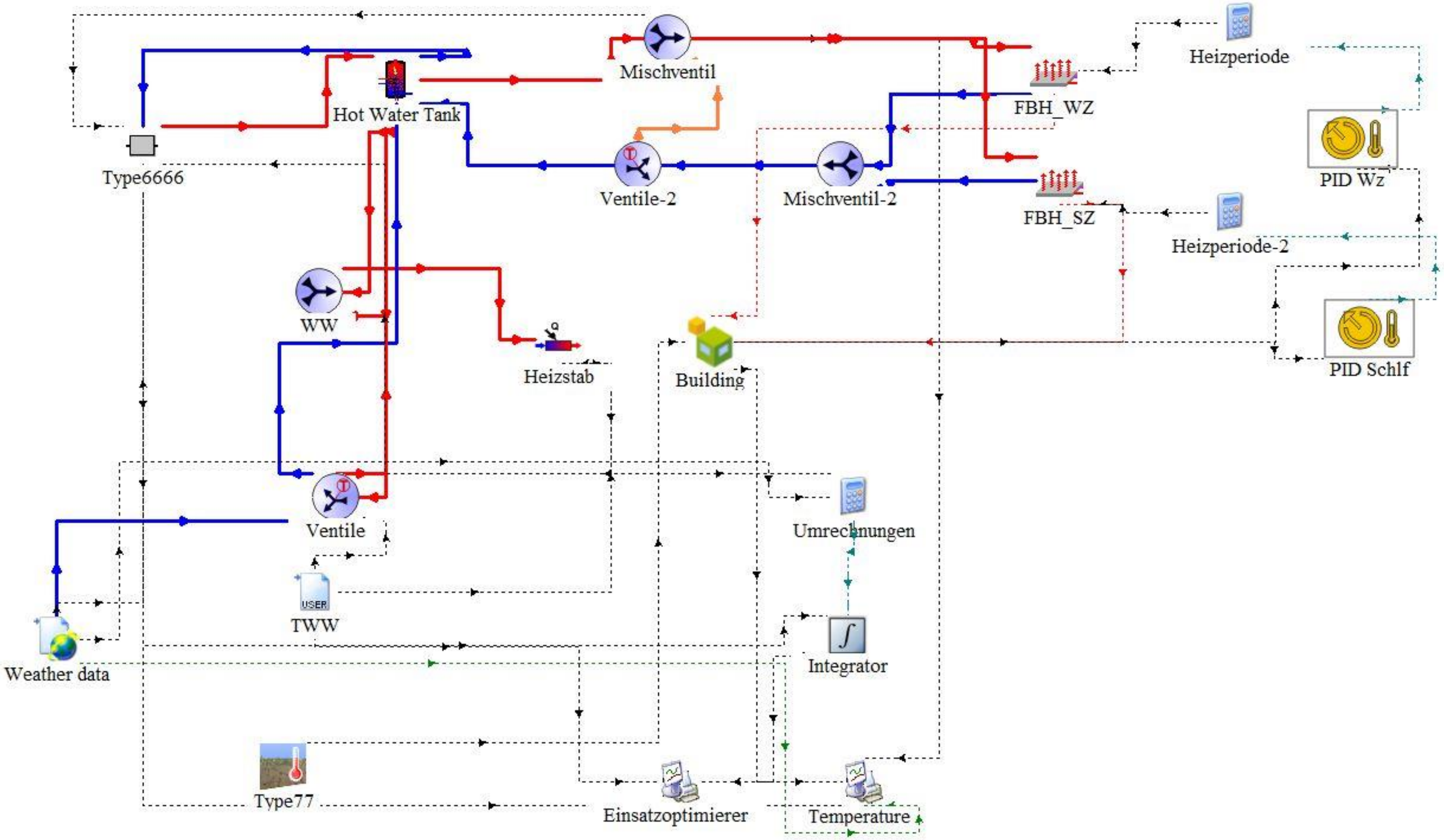

Figure 4: Simulation model in TRNSYS (containing Floor Heating and DHW)

4.5. Simulation model MATLAB

Within the project, the models of HPs and controllers, which are largely based on mathematical principles, are modelled in MATLAB. No different types are required, the equations can be programmed and solved directly in MATLAB. The heat pump was modelled on the basis of manufacturer information and measurement data. The MPC generates an operational plan for 48 hours. It uses a simplified model of the building and the storage and also has access to predictive weather data. This allows the controller to generate an optimised schedule for the heat pump, taking predictions of the electricity prices and the COP into account. By comparing the heat demand of the building with the heat capacity of the storage tank, the operation can be shifted to the most economical periods. In addition, several variables are read and processed in MATLAB, which are transmitted from TRNSYS at each time step. For a more detailed description of the controller, compare [1].

4.6. Exchange of variables

As already mentioned, variables are exchanged between TRNSYS and MATLAB at each time step, the respective variables are listed below.

From TRNSYS to MATLAB:

- Current room temperatures
  Within the project, all buildings will be modelled with two heated zones, one zone with 21 °C (as assumed living zone) and one zone with 18 °C (as assumed sleeping zone). The current temperatures of the zones are transmitted to the controller in order to always maintain thermal comfort.

- Current storage temperatures
  The temperatures in the heat storage tank are transmitted to enable the controller to calculate the available heat capacity. This makes it not only possible to determine how long the heating demand of the building can still be covered but also informs about the available heat capacity before the tank is completely charged.

- Sensor temperatures
  Temperatures that are calculated during the simulation and passed on to the controller, e.g: supply temperature of the heating system, return temperature of the heating system, temperatures of the DHW.

- Mass flow of the heating system
  The current mass flow of the heating system is passed on to the controller at every time step.

From MATLAB to TRNSYS

- Massflow into the heat storage
  Mass flow from the heat pump to charge the heat storage tank.

- Supply temperature into the heat storage
  The outlet temperature of the heat pump that is going into the storage tank.

- Thermal power of the HP
  The thermal power generated from the heat pump (in kWh) for each simulation step.

- Electrical power consumption of the HP
  Calculates the electrical power consumption of the HP (in kWh) for each simulation step.

- COP of the HP
  The Coefficient of Performance (COP) can be determined from the electrical power consumption and thermal power output; it is an important value for the efficiency of the HP.

- Price signal
  MATLAB uses an external electricity price signal, which is used to optimize the operation of the HP. The prices at each time step are an output used for the analysis of the results.

- Price related COP
  A combination of electricity price and COP allows the HP to be controlled in the most economical way, as both costs and efficiency are taken into account for optimization.

- Speed of the HP
  The controller offers the possibility to control both a fixed-speed and a variable-speed HP. Especially in the case of speed variability, this output is interesting for the analysis.

- Electrical power consumption of the heating element
  The heat pump can be dimensioned to suit the heating load of each particular building. In practice, the heat pump is usually slightly undersized, as the highest heating load only occurs very rarely during the year. In this case, heat pumps often have an additional electrical heating element that can be switched on under extreme conditions. The power requirement of this element is important for the efficiency and annual cost of the system.

After the coupling of the models, the system simulations for different scenarios have been carried out and analysed in Action 8.3. The different scenarios result from the amount of simulation models. There are reference buildings in different construction classes for each country of the Greater Region (a total of 45 different building models), different storage systems (PCM and water) in different volumes (300 l to 2000 l), as well as two heat pumps, one in standard operation and one controlled by the MPC developed in Action 8.1. This results in more than 1000 possible combinations. Adding the two possible heating systems (radiator and floor heating) results in an enormous number of potential simulations. The focus was mainly on the existing buildings and possible refurbishment concepts. Some key results of Action 8.3 are presented in subsection 5.

5. Results

In the following chapter, the results of Action 8 will be presented and discussed. Firstly, the results of the individual countries of the Greater Region are presented in combination with radiators as a heating system. Secondly, results in combination with radiant floor heating are analysed. The possible potential of phase change materials (PCM) is also briefly discussed by means of simulations.

As mentioned in the previous chapter, the primary objective of the controller is to minimise operating costs. In order to be able to check the realisation of this objective, the simulation results of Action 8 are presented below.

5.1 Radiator

5.1.1. Germany

The following three tables show the results of a fix-speed heat pump in classical operation, a fix-speed heat pump in controlled operation and a heat pump with variable speed in controlled operation. The subdivision into three tables allows an analysis of the different influences - thus both the effect of speed variability and the pure effect of the controller can be represented.

Since the reference building is an old building from the 1960s, various refurbishment concepts have been modelled within the project - the building shown here complies with the KfW85 [10] standard . After modernisation, the building has a heating load of 7.7 kW (including domestic hot water), and accordingly a 7 kW heat pump was installed, which contains additionally a 3 kW heating element to cover peak loads. A water tank in various volumes was chosen as the heat storage system in order to evaluate the influence of the resulting heat capacity on the results. As shown in Action 6, the volume of the storage has a big effect on the flexibility of the building and therefore also on the efficiency of the controller.

In general, all tables in this chapter contain the electricity consumption, the generated thermal energy and the resulting COP of the HP. Additionally the influence of the heating element is listed: the power consumption as well as the COP in combination with the HP. The last two lines show the electricity costs from the simulation in € and also the average used price in Cents/kWh.

Radiators were maintained as the heating system of the reference building. Corresponding simulations with radiant floor heating systems and PCM storage tanks will also be presented in the course of section 5.

Table 1: Germany – Simulation results for a fix-speed HP in classical operation

	Fix-speed HP in classical operation					
Construction year class	E [1958-1968]					
Refurbishment	KfW85					
Heating load (kW)	5.39 (without DHW); 7.77 (with DHW)					
HP air/water (kW)	7					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	4516	4553	4598	4639	4604	4575
Generated thermal energy HP (kWh)	13542	13600	13742	13824	13807	13762
Seasonal COP (without heating element)	3.00	2.99	2.99	2.98	3.00	3.01
Elec. consumption heating element (kWh)	214	248	175	175	137	257
Seasonal COP (with heating element)	2.91	2.88	2.92	2.91	2.94	2.90
Electricity costs from simulation (€)	1077	1093	1087	1096	1079	1100
Average used price (Cent/kWh)	22.77	22.77	22.77	22.77	22.77	22.77

Table 2: Germany – Simulation results for a fix-speed HP in controlled Operation

	Fix-speed HP in controlled operation					
Construction year class	E [1958-1968]					
Refurbishment	KfW85					
Heating load (kW)	5.39 (without DHW); 7.77 (with DHW)					
HP air/water (kW)	7					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	4767	4778	4784	4788	4750	4760
Generated thermal energy HP (kWh)	13700	13929	14013	14065	14018	14000
Seasonal COP (without heating element)	2.87	2.92	2.93	2.94	2.95	2.94
Elec. consumption heating element (kWh)	159	184	147	145	102	75
Seasonal COP (with heating element)	2.81	2.84	2.87	2.88	2.91	2.91
Electricity costs from simulation (€)	1139	1145	1135	1134	1113	1107
Average used price (Cent/kWh)	23.12	23.08	23.02	22.99	22.94	22.90

Table 3: Germany – Simulation results for a variable speed HP in controlled operation

	Variable speed-HP in controlled operation					
Construction year class	E [1958-1968]					
Refurbishment	KfW85					
Heating load (kW)	5.39 (without DHW); 7.7 (with DHW)					
HP air/water (kW)	7					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	4244	4249	4259	4267	4234	4244
Generated thermal energy HP (kWh)	13595	13693	13776	13877	13877	13966
Seasonal COP (without heating element)	3.20	3.22	3.23	3.25	3.28	3.29
Elec. consumption heating element (kWh)	253	230	231	189	144	108
Seasonal COP (with heating element)	3.08	3.11	3.12	3.16	3.20	3.23
Electricity costs from simulation (€)	1042	1036	1032	1029	1008	999
Average used price (Cent/kWh)	23.17	23.13	22.98	23.09	23.02	22.95

The results presented refer solely to the heating period. In the summer months the heating demand of a residential building is usually too low to analyse the effect on the electricity grid.

In a first step, it is reasonable to compare the results of the two fixed-speed HPs, as they are based on the same HP model. Thus, the effect of the control system can be seen. In controlled operation, it can be observed that both the average price and the absolute electricity costs decrease with increasing storage volume. This was expected and confirms the functionality of the control system - with increasing volume, the storage capacity also rises and the controller has an improved possibility to operate the HP at the lowest possible electricity prices, which leads to cost savings for the consumer.

For the comparison with the results in classical operation, it is of central importance that the two simulations are based on different electricity prices. In Germany, there are constant heat pump tariffs that are cheaper than normal household prices, but also contain so-called "off-times" during which the grid operator can prevent the electricity consumption of the heat pump for a short time to avoid peak loads. However, it is important for the control system that a flexible electricity tariff is available, otherwise cost-optimised control is not possible. Therefore, flexible electricity prices were modelled in Action 7 and already explained in figure 1. These tariffs are in average higher than the offered heat pump tariffs. This is the reason for no cost savings in a direct comparison. However, if renewable energies are increasingly integrated into the electricity mix, incentives should also be provided in the future to consume electricity when the share of renewable energies is relatively high. Accordingly, it can be assumed that the electricity price will become more flexible in the future and that the use of the controller will become more economical.

In addition, the results of a HP with variable speed also provide interesting results. In this case, the controller is not only able to determine when the HP should run, but also at which speed. Compared to the results with a fix-speed HP, this already brings the advantage of not always operating the HP at full speed. Thus it is possible to adapt the power of the HP more effectively to the heating demand of the building. This also explains the lower electricity consumption and the higher annual performance factor.

In addition, these results also confirm the functionality of the controller: with increasing volume, both the average and the absolute price decrease and enable cost savings. In a direct comparison, the overall electricity costs are now lower than with a fix-speed HP in classic operation even if the average price used remains higher due to the structure of the electricity tariffs. Still, due to the lower electrical power requirement, up to 100€ can be saved annually based on the simulation results.

These values also provide an input for the economic analysis within the project in Action 9. [11]

5.1.2. France

The simulations and evaluations were also carried out analogously for the reference buildings in France. The results are presented in the following tables.

Table 4:France – Simulation results for a fix-speed HP in classical operation

	Fix-speed HP in classical operation (night tariff)					
Construction year class	1982-1989					
Refurbishment	According to TUK ARCH (PEF Requirements)					
Heating load (kW)	5.02 (without DHW); 7.33 (with DHW)					
HP air/water (kW)	6					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	4117	4120	4230	4225	4316	4371
Generated thermal energy HP (kWh)	12272	12298	12591	12522	12671	12765
Seasonal COP (without heating element)	2.98	2.98	2.98	2.96	2.94	2.92
Elec. consumption heating element (kWh)	369	431	264	393	182	171
Seasonal COP (with heating element)	2.82	2.80	2.86	2.80	2.86	2.85
Electricity costs from simulation (€)	654	657	634	651	614	620
Average used price (Cent/kWh)	14.58	14.44	14.11	14.10	13.65	13.65

Table 5: France – Simulation results for a fix-speed HP in controlled operation

	Fix-speed HP in controlled operation					
Construction year class	1982-1989					
Refurbishment	According to TUK ARCH (PEF Requirements)					
Heating load (kW)	5.02 (without DHW); 7.33 (with DHW)					
HP air/water (kW)	6					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	4367	4392	4411	4420	4394	4408
Generated thermal energy HP (kWh)	12427	12477	12619	12658	12688	12894
Seasonal COP (without heating element)	2.85	2.84	2.86	2.86	2.89	2.93
Elec. consumption heating element (kWh)	284	309	231	234	152	156
Seasonal COP (with heating element)	2.73	2.72	2.77	2.77	2.82	2.86
Electricity costs from simulation (€)	696	690	665	663	639	640
Average used price (Cent/kWh)	14.96	14.68	14.33	14.25	14.06	14.02

Table 6: France – Simulation results for a variable speed HP in controlled operation

	Variable speed-HP in controlled operation					
Construction year class	1982-1989					
Refurbishment	According to TUK ARCH (PEF Requirements)					
Heating load (kW)	5.02 (without DHW); 7.33 (with DHW)					
HP air/water (kW)	6					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	3934	3967	4035	4077	4100	4131
Generated thermal energy HP (kWh)	12344	12400	12503	12575	12625	12685
Seasonal COP (without heating element)	3.14	3.13	3.10	3.08	3.08	3.07
Elec. consumption heating element (kWh)	362	375	340	310	212	210
Seasonal COP (with heating element)	2.96	2.94	2.94	2.94	2.98	2.97
Electricity costs from simulation (€)	642	637	628	625	607	608
Average used price (Cent/kWh)	14.94	14.67	14.35	14.25	14.08	14.01

The results confirm the analysis presented for the previous German simulations. One important difference can be found in the structure of the HP tariff for classical operation. Other than the German tariff, the French one does not represent a constant price, but a "night tariff", which is intended to provide an incentive to consume electricity potentially at night. These lower prices refer to a generally lower electricity demand during nights. Accordingly, it also explains why costs decrease with increasing storage volume - the higher the available storage capacity, the more often the generation of heat can be avoided during the day and the cheaper night tariff can be exploited primarily.

However, the results also show the functionality of the control system. With increasing storage volume, significant costs can be saved, especially in combination with a variable speed HP. It also shows that both in Germany and in France the savings in the average used price are rather small with increasing storage volume (< 1 Cent/kWh). The following results for Belgium show that this refers more to the structure of the electricity tariffs than to the effectiveness of the controller.

5.1.3. Belgium

Table 7: Belgium – Simulation results for a fix-speed HP in classical operation

	Fix-speed HP in classical operation (night tariff)					
Construction year class	Before 1945					
Refurbishment	nach TUK ARCH (Min. Requirements)					
Heating load (kW)	2.01 (without DHW); 4.41 (with DHW)					
HP air/water (kW)	4					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	2379	2435	2482	2536	2550	2569
Generated thermal energy HP (kWh)	6826	7020	7069	7174	7195	7255
Seasonal COP (without heating element)	2.87	2.88	2.85	2.83	2.82	2.82
Elec. consumption heating element (kWh)	177	94	101	82	43	23
Seasonal COP (with heating element)	2.74	2.81	2.78	2.77	2.79	2.81
Electricity costs from simulation (€)	493	487	468	475	472	471
Average used price (Cent/kWh)	19.29	19.26	18.12	18.14	18.20	18.17

Table 8: Belgium – Simulation results for a fix-speed HP in controlled operation

	Fix-speed HP in controlled operation					
Construction year class	Before 1945					
Refurbishment	nach TUK ARCH (Min. Requirements)					
Heating load (kW)	2.01 (without DHW); 4.41 (with DHW)					
HP air/water (kW)	4					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	2311	2310	2290	2290	2301	2336
Generated thermal energy HP (kWh)	6710	6776	6799	6819	6848	6923
Seasonal COP (without heating element)	2.90	2.93	2.97	2.98	2.98	2.96
Elec. consumption heating element (kWh)	98	64	48	48	23	20
Seasonal COP (with heating element)	2.83	2.88	2.93	2.94	2.96	2.95
Electricity costs from simulation (€)	445	424	413	411	402	407
Average used price (Cent/kWh)	18.47	17.86	17.66	17.58	17.30	17.28

Table 9: Belgium – Simulation results for a variable speed HP in controlled operation

	Variable speed-HP in controlled operation					
Construction year class	Before 1945					
Refurbishment	nach TUK ARCH (Min. Requirements)					
Heating load (kW)	2.01 (without DHW); 4.41 (with DHW)					
HP air/water (kW)	4					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	2051	2093	2098	2120	2167	2201
Generated thermal energy HP (kWh)	6768	6805	6840	6874	6889	6958
Seasonal COP (without heating element)	3.30	3.25	3.26	3.24	3.18	3.16
Elec. consumption heating element (kWh)	137	102	66	55	28	19
Seasonal COP (with heating element)	3.16	3.15	3.19	3.19	3.15	3.14
Electricity costs from simulation (€)	405	394	381	381	379	382
Average used price (Cent/kWh)	18.51	17.95	17.61	17.52	17.27	17.21

In the Belgian simulation results, it can be demonstrated that the controller can also be economical in a direct comparison of the two fixed-speed HPs. This can be explained based on the Belgian electricity tariff used in the simulations. The tariff has a much higher flexibility, that enables the controller to use significantly cheaper price signals for the operation of the HP. This can also be seen in the difference between the average electricity price used and the increasing storage volume – the difference is noticeably higher than in the results presented for Germany and France.

The higher flexibility within electricity prices is described more detailed in section 5.1.5. However, the results show that a certain flexibility must be present in the price signal to make the application of the controller more economical. With the increasing integration of fluctuating renewables, it can be assumed that the electricity price will show stronger fluctuations in the future, which will be very beneficial to the developed control system.

5.1.4. Luxembourg

Table 10: Luxembourg – Simulation results for a fix-speed HP in classical operation

	Fix-speed HP in classical operation (night tariff)					
Construction year class	New construcion - L					
Refurbishment	None					
Heating load (kW)	2.18 (without DHW); 4.49 (with DHW)					
HP air/water (kW)	4					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	1794	1857	1902	1950	1945	1976
Generated thermal energy HP (kWh)	5179	5358	5448	5567	5511	5601
Seasonal COP (without heating element)	2.89	2.89	2.86	2.85	2.83	2.83
Elec. consumption heating element (kWh)	180	100	91	31	79	51
Seasonal COP (with heating element)	2.71	2.79	2.78	2.83	2.76	2.79
Electricity costs from simulation (€)	261	255	257	254	259	259
Average used price (Cent/kWh)	13.22	13.03	12.90	12.82	12.80	12.78

Table 11: Luxembourg – Simulation results for a fix-speed HP in controlled operation

	Fix-speed HP in controlled operation					
Construction year class	New construcion - L					
Refurbishment	None					
Heating load (kW)	2.18 (without DHW); 4.49 (with DHW)					
HP air/water (kW)	4					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	1941	1958	1993	2015	2012	2036
Generated thermal energy HP (kWh)	5306	5436	5572	5628	5602	5672
Seasonal COP (without heating element)	2.73	2.78	2.80	2.79	2.78	2.79
Elec. consumption heating element (kWh)	115	54	20	20	10	8
Seasonal COP (with heating element)	2.64	2.73	2.78	2.78	2.78	2.78
Electricity costs from simulation (€)	276	265	260	262	258	260
Average used price (Cent/kWh)	13.42	13.17	12.92	12.87	12.76	12.72

Table 12: Luxembourg – Simulation results for a variable speed HP in controlled operation

	Variable speed-HP in controlled operation					
Construction year class	New construcion - L					
Refurbishment	None					
Heating load (kW)	2.18 (without DHW); 4.49 (with DHW)					
HP air/water (kW)	4					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	1773	1784	1823	1845	1846	1869
Generated thermal energy HP (kWh)	5422	5486	5567	5625	5593	5663
Seasonal COP (without heating element)	3.06	3.08	3.05	3.05	3.03	3.03
Elec. consumption heating element (kWh)	126	73	36	26	12	7
Seasonal COP (with heating element)	2.92	2.99	3.01	3.02	3.02	3.02
Electricity costs from simulation (€)	255	245	241	241	237	239
Average used price (Cent/kWh)	13.43	13.19	12.96	12.88	12.76	12.74

The reference building from Luxembourg is a new construction, and the thermal state of the building is correspondingly good, which is visible in the very low heating demand. In combination with the comparatively cheap electricity price in Luxembourg, this leads to quite low annual electricity costs for the heating system. Therefore, the potential for savings in the considered case is relatively low. This could significantly change, as soon as share of renewables rises and the structure of the tariff contains a higher flexibility. Nevertheless, the results basically confirm all the effects of the control system described above.

5.1.5. Analysis

The results presented confirm the basic function of the control system: on the one hand, the average price used is below the average electricity price (Germany: 23.5 cents/kWh; France: 15.7 cents/kWh; Belgium: 20.7 cents/kWh; Luxembourg: 14 cents/kWh) and, on the other hand, the used prices decrease with increasing storage capacity. Furthermore, the results also illustrate the different potentials of the control system, which are directly related to the structure of electricity prices in the respective countries. In Germany, the savings are relatively small compared to the average electricity price (maximum 0.6 cents/kWh), while in Belgium up to 3.5 cents/kWh can be saved. In order to estimate the reason for these differences, a detailed look at the structure of the various electricity prices, is useful. (see Figure 5)

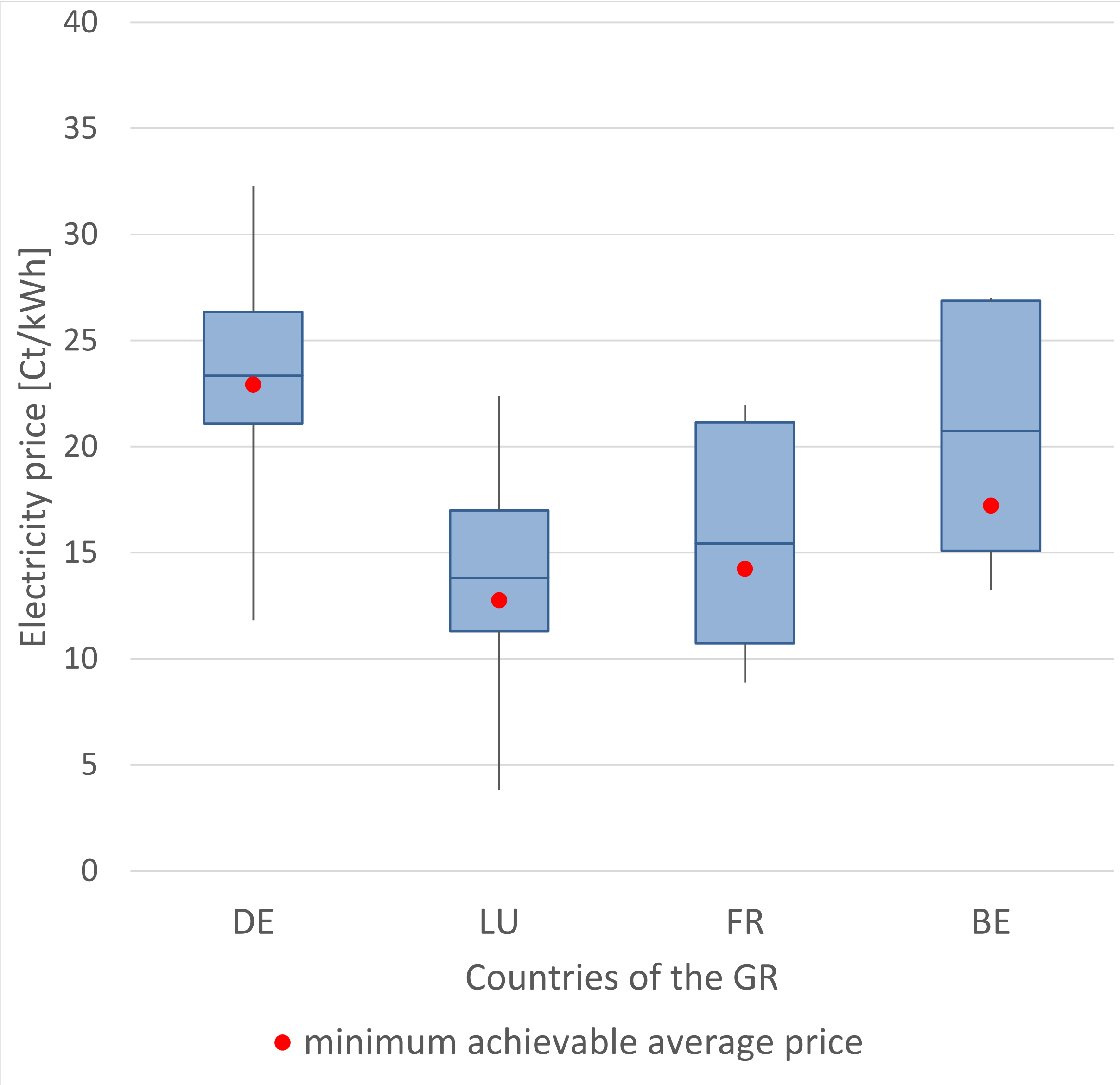

Figure 5: Electricity tariffs for the different countries of the Greater Region and minimum achievable price out of the simulations with the Controller

The figure shows the distribution of the relevant electricity prices for the four different countries of the Greater Region. The fluctuations within the electricity price in Germany and Luxembourg are rather small, since 90% of the values are within a fairly small range. For the controller, this means that the tariffs do not exhibit a big difference in the prices and consequently it's difficult to ensure real price savings. The figure also shows that the Belgian tariff has a much greater spread, which means that cost savings can be better achieved by the controller.

The minimum achievable average prices in combination with the controller are shown as a red dot in the figure. This definitely confirms that in each simulation the used prices could be lowered below the median, which clarifies that the controller works well on a simulation basis.

As a preliminary conclusion from the first simulation results and the price structures of the various countries in the Greater Region, it can therefore be concluded that a flexible tariff with sufficient price fluctuation should be available as the basis for the controller. If this is the case, the developed controller has the potential to ensure cost savings, if combined with a heat storage. A detailed economic classification of the results takes place in work package 9.

5.2. Surface Heating

In principle, the efficiency of HPs depends on the temperature difference between the heat source and the heat sink. This explains why heat pumps are used primarily in combination with surface heating systems (especially radiant floor heating (RFH)). The required flow temperature is significantly lower due to the considerably higher surface for heat exchange. The combination of heat pump and floor heating is therefore a solution that is being implemented more and more frequently, mainly in new buildings. Conversely, when renovating buildings, it is very expensive to replace radiators with RFH, as it requires a core refurbishment. To this point, only results have been presented in combination with radiators, radiant floor heating as a heating system will also be investigated accordingly.

In order to be able to assess this in the context of the previous results, the simulations had identical boundary conditions as the previously presented ones - with the only difference that floor heating systems and not radiators were used. Furthermore, only the results of a variable speed HP in combination with the controller are shown in this section.

Table 13: Germany – Simulation results for a variable speed HP in controlled operation with surface heating

	Variable speed-HP in controlled operation					
Construction year class	E [1958-1968]					
Refurbishment	KfW85					
Heating load (kW)	5.39 (without DHW); 7.7 (with DHW)					
HP air/water (kW)	7					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	4131	4140	4139	4124	4081	4096
Generated thermal energy HP (kWh)	14693	14845	15024	15109	15104	15219
Seasonal COP (without heating element)	3.56	3.59	3.63	3.66	3.70	3.72
Elec. consumption heating element (kWh)	235	223	219	211	195	186
Seasonal COP (with heating element)	3.42	3.45	3.50	3.53	3.58	3.60
Electricity costs from simulation (€)	1015	1013	1012	1005	988	987
Average used price (Cent/kWh)	23.25	23.22	23.22	23.18	23.11	23.05

Table 14: France - Simulation results for a variable speed HP in controlled operation with surface heating

	Variable speed-HP in controlled operation					
Construction year class	1982-1989					
Refurbishment	According to TUK ARCH (PEF Requirements)					
Heating load (kW)	5.02 (without DHW); 7.33 (with DHW)					
HP air/water (kW)	6					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	3628	3648	3721	3777	3811	3843
Generated thermal energy HP (kWh)	13088	13205	13442	13570	13643	13775
Seasonal COP (without heating element)	3.61	3.62	3.61	3.59	3.58	3.58
Elec. consumption heating element (kWh)	286	282	228	212	194	189
Seasonal COP (with heating element)	3.42	3.43	3.46	3.46	3.45	3.46
Electricity costs from simulation (€)	582	568	550	550	547	550
Average used price (Cent/kWh)	14.87	14.45	13.93	13.79	13.66	13.64

Table 15: Belgium - Simulation results for a variable speed HP in controlled operation with surface heating

	Variable speed-HP in controlled operation					
Construction year class	Before 1945					
Refurbishment	According to TUK ARCH (Min. Requirements)					
Heating load (kW)	2.01 (without DHW); 4.41 (with DHW)					
HP air/water (kW)	4					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	1905	1912	1933	1944	1968	2000
Generated thermal energy HP (kWh)	7081	7138	7245	7319	7362	7476
Seasonal COP (without heating element)	3.72	3.73	3.75	3.76	3.74	3.74
Elec. consumption heating element (kWh)	396	391	380	364	314	283
Seasonal COP (with heating element)	3.25	3.27	3.30	3.33	3.36	3.40
Electricity costs from simulation (€)	432	425	421	418	408	406
Average used price (Cent/kWh)	18.77	18.45	18.20	18.11	17.88	17.78

Table 16: Luxembourg - Simulation results for a variable speed HP in controlled operation with surface heating

	Variable speed-HP in controlled operation					
Construction year class	New construction - L					
Refurbishment	None					
Heating load (kW)	2.18 (without DHW); 4.49 (with DHW)					
HP air/water (kW)	4					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	1577	1584	1623	1648	1667	1692
Generated thermal energy HP (kWh)	5682	5791	5956	6054	6115	6216
Seasonal COP (without heating element)	3.60	3.66	3.67	3.67	3.67	3.67
Elec. consumption heating element (kWh)	211	196	169	154	116	106
Seasonal COP (with heating element)	3.30	3.36	3.42	3.45	3.49	3.52
Electricity costs from simulation (€)	239	236	234	235	229	230
Average used price (Cent/kWh)	13.37	13.26	13.06	13.04	12.84	12.79

Several findings can be drawn from the results. First of all, the rising COP is noticeable - this was to be expected and is the main reason to use a surface heating system in combination with the HP. The efficiency increases significantly due to lower supply temperatures. The increase in the COP without a heating element is particularly noteworthy, as this represents the pure operation of the heat pump. Looking at the COP with heating element, it is visible that the increase is smaller. This is related to the generation of DHW. The flow temperatures can be reduced to around 30 °C - 40 °C by using a floor heating system. Accordingly, the maximum temperature in the storage tank also decreases. However, since DHW with at least 45 °C must still be available, a heating element is used in these simulations which reheats electrically the DHW-flow until at least 45 °C. Accordingly, the influence of the heating element is much stronger than in the simulations with radiators.

It turns out, that in 3 out of 4 cases a cost reduction can be achieved by using floor heating. The higher COP reduces the electrical power requirement and thus also the absolute electricity price. In the Belgian building, on the other hand, which has a quite small area, the share of the heating element in the total thermal energy generated is pretty high over the year, which means that the total costs increase. This is based on a higher share of the energy for DHW compared to the whole energy demand of the building. In this case, a different solution would be aimed for in the implementation and the heat pump might be dimensioned higher in order to minimise the inefficient use of the heating element.

Overall, the results confirm the expectations. Better efficiency and greater overall flexibility can contribute to a further reduction in costs.

5.3. PCM

All results presented so far were carried out with a water storage tank. As this is by far the most common system for heat storage in residential buildings in the GR, the results also reflect the greatest relevance. Nevertheless, storage tanks with PCM (Phase Change Material) will also be considered in the following, as they could become more relevant in the future and fit well with the objectives of the project.

The advantage of PCM consists in its properties during phase change - it is possible for these materials to release or absorb very large amounts of energy in rather small temperature differences. The phase transition that is considered within the project is the transition between solid and liquid, since the volume change of the substances can usually be controlled quite well. Thus it is possible to guarantee larger amounts of energy in the same volumes in comparison to pure water tanks. This means an achievement of higher flexibility can be obtained by introducing PCM, as they offer a larger storage capacity. This can lead to lower overall costs in combination with the developed control system. Particularly when renovating old buildings, it is often not possible to replace the storage system in favour of a significantly larger one due to space constraints. By introducing PCM, however, the available capacity could also be increased with the existing volume.

The selection of the PCM is also important. There are many different materials on the market that can be selected and used - the decisive criterion is usually the temperature at which the selected material undergoes its phase change. It is important for a good efficiency of the system that the PCM passes through this temperature range as often as possible. Thus, the properties can be used frequently during the phase change. In this project and with the selected heating system, it is therefore advisable to select a temperature that corresponds approximately to the supply temperature of the heating system. Additionally, it is important to place the PCM inside the storage tank within the area that also locates the outlet to the heating system, since the greatest temperature fluctuations occur there.

The considered storage is basically a water storage tank that contains PCM in various geometries. Preliminary investigations have confirmed relatively clearly that spheres represent the best shape, which was to be expected, since the best A/V ratio is present (area-to-volume) and thus a maximum heat input can be guaranteed. Furthermore, the diameter of the individual spheres, how many of them are integrated into the system and the position in the tank have to be determined. The middle tank area was selected due to the temperature fluctuations and a value of about 0.7 balls per litre of water was defined in a preliminary study; one ball has a diameter of 7.5 cm.

As a further step, it was necessary to integrate the modified storage model into the controller. Accordingly, the underlying control model was extended by the properties of PCM. This is necessary because the integration of PCM achieves a new storage capacity and this capacity cannot be assumed to be constant over the temperature compared to water. The controller must not only be able to calculate the currently available capacity, but must also be able to forecast the course at different temperatures on the basis of the PCM's material data.

Within TRNSYS, the changes are limited to the exchange of the storage system (from Type340 to Type840). In the following, the results of a water tank with PCM in the German KfW-85 building in combination with radiators as heat dissipation system are presented. As a comparison, the same simulation results are also listed again with a pure water tank.

Table 17: Germany - Simulation results for a variable speed HP in controlled operation with PCM storage

	Variable speed-HP in controlled operation					
Construction year class	E [1958-1968]					
Refurbishment	KfW85					
Heating load (kW)	5.39 (without DHW); 7.7 (with DHW)					
HP air/water (kW)	7					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	4117	4102	4107	4085	4072	4069
Generated thermal energy HP (kWh)	13824	13868	13947	13919	13889	13901
Seasonal COP (without heating element)	3.36	3.38	3.40	3.41	3.41	3.42
Elec. consumption heating element (kWh)	334	244	154	121	85	72
Seasonal COP (with heating element)	3.18	3.25	3.31	3.34	3.36	3.37
Electricity costs from simulation (€)	1039	1013	990	975	959	953
Average used price (Cent/kWh)	23.34	23.31	23.23	23.18	23.07	23.01

Table 18: Germany - Simulation results for a variable speed HP in controlled operation with water storage

	Variable speed-HP in controlled operation					
Construction year class	E [1958-1968]					
Refurbishment	KfW85					
Heating load (kW)	5.39 (without DHW); 7.7 (with DHW)					
HP air/water (kW)	7					
Volume storage tank (l)	300	500	800	1000	1500	2000
Electricity consumption HP (kWh)	4244	4249	4259	4267	4234	4244
Generated thermal energy HP (kWh)	13595	13693	13776	13877	13877	13966
Seasonal COP (without heating element)	3.20	3.22	3.23	3.25	3.28	3.29
Elec. consumption heating element (kWh)	253	230	231	189	144	108
Seasonal COP (with heating element)	3.08	3.11	3.12	3.16	3.20	3.23
Electricity costs from simulation (€)	1042	1036	1032	1029	1008	999
Average used price (Cent/kWh)	23.17	23.13	22.98	23.09	23.02	22.95

The results illustrate the effect of the PCM and correspond to expectations. For all investigated volumes, costs can be saved in comparison to pure water storage. This is mainly due to the rising COP, which ensures that electricity consumption is reduced. As already mentioned in the previous chapters, the fluctuation in the used German electricity price is comparatively low, therefore the controller tends to optimize the COP with increasing volume. Overall, the cost savings that can be achieved are still rather low (max. up to approx. 50€ per year), but the potential of phase change materials is still evident. The effect of the PCM would be even more pronounced if the electricity price would contain a higher variability. Nevertheless, the results confirm the interesting approach of PCM with regard to the project objectives. Especially for refurbishments in existing buildings, the introduction of PCM can be an interesting alternative to the complete replacement of the storage.

6. Conclusion

Within Action 8, a large number of simulations could be carried out and analysed, the most important results were presented in the previous sections. Overall, it can be said that the functionality of the control system could be demonstrated at simulation level. In all the results considered, the controller is able to reduce the average electricity price used by the heat pump with increasing storage volume and accordingly higher storage capacity. In addition, the annual coefficient of performance and thus the efficiency of the heat pump can be improved.

Compared to a classically operated fix-speed HP, which can be operated at lower tariffs in all GR countries, a controlled fix-speed HP only allows savings in Belgium. However, this is also due to the underlying electricity tariffs, which currently have too little fluctuations. This challenges the control system to really operate the HP in cheaper periods. Since the classic HP tariffs are on average lower than the flexible tariffs, no cost savings are possible in the most cases. Nevertheless, the structure and flexibility of electricity prices will probably change over the next few years with the increasing integration of renewable energies. This would improve the efficiency of the controller.

However, looking at variable-speed HPs in controlled operation, there are further advantages of the controller. In this case, the frequency and thus the current electricity consumption of the HP can be controlled. A feasibility analysis of the results will take place in Action 9.

The efficiency of the system can be further increased by using floor heating instead of radiators. The COP of heat pumps can thus be increased by lower supply temperatures, thus reducing electricity consumption. The simulations carried out confirm this approach - the flexibility of the overall system can thereby also be further increased, which supports the potential of the controller.

In the last chapter, the influence of PCM, which can be integrated into the water storage tank in the form of spheres, could also be demonstrated. By increasing the storage capacity, a further increase in flexibility can be achieved, which can lead to further cost savings. However, since PCM is also more expensive compared to water, this does not necessarily mean that the presented system is also more economical nowadays. Still, for the expected developments in the electricity tariffs, such storages can be promising in the future.

Overall, a control system could be developed and connected to the other models in the project within Action 8. Its functionality could clearly be demonstrated based on simulation results. Accordingly, all tasks could be completed within the project duration and serve as inputs for subsequent actions. An assessment of the economic viability of the scenarios examined is carried out in Action 9. However, on the basis of the simulation results, it can already be said that a future “flexibilisation” of electricity prices on the basis of the share of renewable energy would be desirable and would be very supportive to the control system. Within the project, the control system will also be examined in a field test in order to confirm the simulation results in a real application.

7. References

[1] S. Röhrenbeck, A. Benzarti, W.H. Wellßow, K. Maar, P. Hauffe, J. Maul, M. Pahn, A. Tersluisen, H. Gündra (Eds.), Prädiktive Betriebsoptimierung drehzahlvariabler Wärmepumpen in Kombination mit preisvariablen Stromtarifen, 2016.

[2] Barbara Dröschel, Andreas Weber, Energiewirtschaftliche Rahmenbedingungen und Marktdaten für den Betrieb von Wärmepumpen in der Großregion, 2019. http://www.izes.de/sites/default/files/publikationen/PtH4GR2ID_Aktion%207%20energiewirtschaftl.%20Rahmen.pdf (accessed 29 March 2021).

[3] TABULA. http://webtool.building-typology.eu/#bm.

[4] MathWorks, MATLAB.

[5] TRANSSOLAR, TRNSYS.

[6] Michael Wetter, Thierry S. Nouidui and Philip Haves, Building Controls Virtual Test Bed: BCVTB.

[7] Trimble, SketchUp.

[8] DIN EN 12831: Energetische Bewertung von Gebäuden – Verfahren zur Berechnung der Norm-Heizlast.

[9] Solar Heating and Cooling Programme, Solar Combisystems: SHC Task 26. http://task26.iea-shc.org/.

[10] KfW, Kreditanstalt für Wiederaufbau. https://www.kfw.de/kfw.de.html.

[11] Dennis Aldenhoff, Björn-Martin Kurzrock, Feasibility Study of the Heat Pump Storage System: Final Report, 2020. http://www.pth4gr2id.com/ (accessed 16 December 2020).