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Solar PV driven **DC Heat Pump** assisted by **PCM** storage

Design and sizing

Guidelines

Thermal energy generation system proposed at the project:

HEAT4COOL

Smart building retrofitting complemented by solar assisted heat pumps integrated within a self-correcting intelligent building energy management system

Grant Agreement No: 723925

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Table of contents

1 SYSTEM DESIGN

The second proposed thermal energy generation system at the Heat4Cool project consists in the combination of an air source DC driven heat pump supplied by solar photovoltaic together with PCM (Phase Change Materials) storage.

The solar panels generate DC electricity from the solar radiation controlled and optimized by the MPPT (Maximal Power Point Track) carried out by the inverter. Nowadays inverters integrate already this component able to find the optimal voltage for the PV modules strings in order to maximize the electrical energy production. This electrical energy produced at the optimal voltage is converted or inverted to the required DC or AC voltage for its use.

The air source DC Heat Pump uses this renewable electrical production in DC to generate the hot water used to satisfy the DHW (Domestic Hot Water) and heating demands. Since the solar availability and consequently the DC Heat Pump production does not match the thermal demand (in both time and power) PCM storage is used in order to store the excess of solar thermal energy in the moments of greater production and use it after in the moments of greater demand.

The DC Heat Pump can be also operated in cooling mode, producing cooling thermal energy which is used for satisfying the cooling demand. In order to use this operation mode, the cooling demand must be sufficiently important in order to make it profitable to adapt the facility for being able to satisfy the cooling demand.

The system must be completed with a Back-up system, in order to ensure the demand satisfaction even if there is a lack of solar radiation, which drives the heat production or if the main components cannot be used due to any reason as could be the maintenance. This back-up system can be also designed to operate together with the renewable system proposed, being the renewable system responsible for satisfying a constant and base demand and the back-up system satisfying the demand peaks happened over this base demand.

Figure 1 shows a scheme of the proposed system with the main required components.

Following these main components and their subsystems are described.

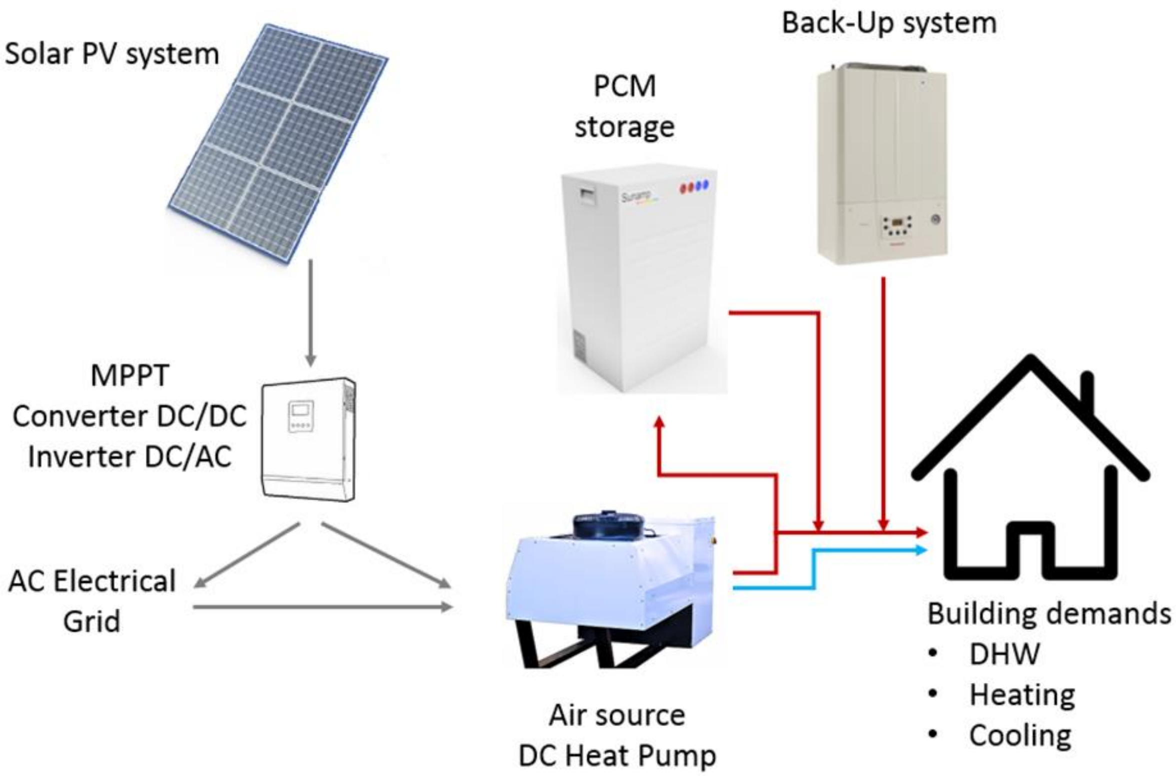


Figure 1. Scheme of the system Solar PV + DC Heat pump + PCM storage.

1.1 Solar PV system design

The solar photovoltaic system is designed as usually done for such a system. The system comprises mainly the solar PV modules and also all the required auxiliary devices as the inverter/converter integrating the MPP tracker, and the protection boxes.

Both monocrystalline and polycrystalline technologies can be suitable for this proposed system. Monocrystalline modules have greater efficiency and thus they are able to produce more energy in the same surface, however they are more expensive what means greater investment costs. Polycristalline panels have slightly lower efficiency but also lower cost. A factor to be considered in the module efficiency (understood as power per surface unit) is the cell density in the solar glass, since a panel with high efficiency cells but with low cell density in the glass could generate less power per surface unit than one with lower cell efficiency but with greater cell concentration.

In the solar system design it has also to be taken into account the municipal and national regulations regarding the installation of these facilities. These can include for example restrictions due to aesthetical issues as the obligation to integrate the panels in the sloped roof surface, what imposes the collectors slope and orientation. Nowadays, there are PV panels available on the market with special appearance in order to make them easily integrated in building envelopes.

Thus the selection of mono- or polycrystalline modules depends on several aspects as the required solar production versus the available surface, aesthetic reasons, etc. Depending on the case study, the designers must decide within the available possibilities, based in energetic and economic calculations if necessary.

A component required for maximizing the solar field production is the MPP tracker, which determines the voltage for the modules strings in order to obtain the maximal electricity production. This component is nowadays already integrated in almost all the solar inverters.

The connection between the PV panels, the inverter to AC and the converter to DC for the Heat Pump power supply consists in a device inverter/converter which furthermore integrates the MPP tracker. This device is connected directly to the PV panels strings and is able to provide AC electricity to the building grid and DC electricity for the DC Heat Pump. There are products capable of being configured in this way or alternatively conventional DC/AC inverter together with an additional converter with voltage controller for determining the required voltage for the DC Heat Pump can be also utilised. However the cost of the first ones can be prohibitive, especially in comparison to the relatively low cost of the DC to AC conversion devices which efficiency is furthermore generally above 96% up to 99% for the best performing products.

An additional consideration should be that any set-up to produce both AC and DC outputs achievable with the currently existing equipment would not allow the use of individual panel MPPT technology, so that in a situation with shading or multiple solar panel orientations and inclinations the benefit provided by the MPPT would be far greater than that one of avoiding inverting from DC to AC power.

Finally, protection boxes are necessary in both sides of the inverter, this is in the DC side connected to the solar panels and in the AC side connected to the grid, enabling the disconnection and the electrical protection against high voltages or currents.

1.2 Air source DC Heat Pump design

The air source DC Heat Pump uses a refrigerant cycle driven by a DC compressor in order to pump heat from a cold source to a warmer one. Other components integrated in the unit as the electronic valve and the fan are also supplied by DC current.

Additionally to the heat pump, it is also needed the circulating pump of the water circuit, which could be already integrated inside the unit housing. In this case, the consumption of the circulating pump would be also from the DC electricity supplied by the PV panels.

The air source heat pump extracts the heat in the evaporator from the ambient air, through a tube and fins heat exchanger where the refrigerant is circulating inside the tubes and the air propelled by the fan through the external side of the tubes and the fins. Therefore the evaporator needs to be placed in the external ambient.

At the condenser the refrigerant delivers heat to the water circulating in the secondary side of the heat exchanger.

The temperature conditions in the two temperature sources determine the unit performance, therefore it is convenient to get the most favourable temperature conditions as possible at the evaporator and condenser. For this reason it must be avoided the introduction of additional temperature losses between the source temperatures and the unit heat exchangers, so it is desired to take unaffected ambient air in the evaporator and directly the demand water circuit in the condenser. In the same way, the required temperature for satisfying the demand must be carefully defined. Therefore low temperature heating emission systems at the heated spaces result more interesting than those ones of high temperature, as well as it has to be analysed if it is worth to try covering the DHW and heating demand completely with the heat pump or only partially, introducing a preheating until a defined temperature level and then completing the heating process of the heat transfer fluid with an auxiliary system.

The whole system and consequently the DC Heat Pump can be designed for two different heat demand ratios to be satisfied by the renewable system:

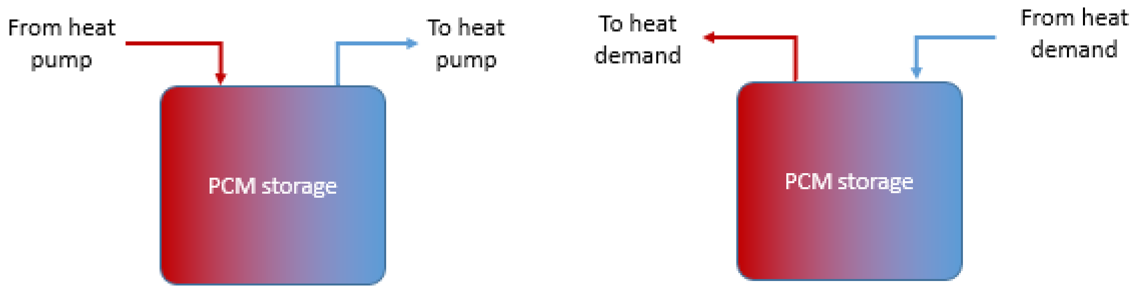
- Cover all or almost all the heat demand, what implies the DC heat pump being able to produce heat at the maximal required temperature by both the DHW and heating demand.
- Cover partially the heat demand by being the DC heat pump able to produce heat until a temperature lower than the maximal required and then the heat demand being completed by an auxiliary system.

As said above, the temperature conditions in the temperature sources determine the unit performance, so that the higher the production temperature of the heat pump, the lower its efficiency. Therefore, designing the system with the first strategy means that the heat pump produces a greater amount of energy but at a lower efficiency, while in the second one the heat pump produces less energy and covers only partially the demand but with a higher efficiency.

Water circuit connection

In the Heat4Cool proposed system the hot water produced is directly sent to satisfy the demand and if there is any surplus, this is sent to the PCM storage.

The PCM storage is not like a stratified tank with several inlet and outlet heights. It has one inlet and one outlet. However, since the HTF (Heat Transfer Fluid) delivers heat to the storage during the charge process, the PCM material closer to the entry zone is more charged than that one closer to the HTF exit zone. Therefore, it results interesting for the discharge process to invert the flow, entering the storage through the connection which corresponds to the outlet during the charge process and exiting through the connection for the inlet during the charge (Figure 2).



a) Storage charging process. b) Storage discharging process.

Figure 2. Flow direction of the HTF during the charge and discharge processes.

Thus the HTF exits the storage after exchanging heat with the more charged PCM material.

In the case of an old facility retrofitting it may be interesting installing a heat exchanger between the water circuit of the DC Heat Pump and the existing heating demand circuit of the building. This implies a greater investment cost as well as a decrease of the efficiency due to the temperature level losses introduced in the heat exchanger and consequently also greater operation costs, but in this case of using an old facility the overall system would acquire more consistency. Thus, the heat exchanger isolates the old heating system which otherwise could harm the centralized system, e.g. with piping losses in the heating circuit that would empty a new centralized circuit, or due to the debris and particles present in the old heating circuit that may damage the new centralized system. Figure 3shows the scheme of a centralized DC Heat Pump generation system with separation heat exchangers to each circuit of the old heating systems at each space of the building.

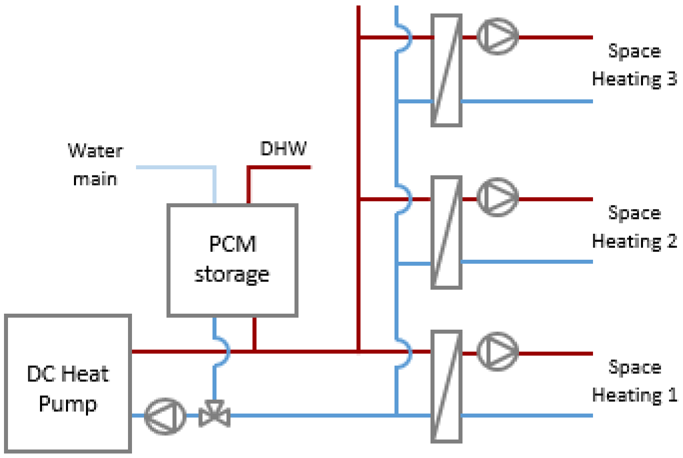


Figure 3. Scheme of Space Heating system with circuit isolating heat exchangers.

<u>Cooling mode operation</u>

The DC heat pump unit could also work in cooling mode if reversible. In this mode, the heat exchanger to the ambient air is used as condenser and the refrigerant-water heat exchanger works as the evaporator, extracting heat from the water which is delivered to the ambient air through the condenser.

In order to be this operation mode profitable, the cooling demand must be great enough in order to make worth the additional investment effort of a reversible unit and of the modifications in the facility for enabling the delivery of also cooling energy.

Unit placement

Finally, the heat pump requires the evaporator to be placed outdoor. The evaporator probably is integrated in the same housing of the rest of the unit. In any case, if it is not integrated, the distance between the evaporator and the rest of the circuit should be minimized in order to reduce the refrigerant piping length (and thus the thermal losses and refrigerant mass charge of the device), so that probably the unit should be installed also outdoor. The space availability and national or municipality regulations (due to aesthetic, noise or any other kind of issue) must be checked.

1.3 PCM storage design

The thermal storage enables to disconnect the thermal demand from the thermal energy generation, in both aspects time and power.

The heat from the DC Heat pump powered by the solar panels is obviously produced when the solar radiation is available, but the heat demand probably does not match with this production in time and power, therefore it is convenient to use a storage in order to store the heat produced during the solar radiation availability and use it after when the heat demand occurs.

The volume of PCM storage must be determined accordingly to the DC Heat Pump capacity and the heat demand. This must be enough to store all the daily heat production from the DC Heat Pump but not a too much volume so that the number of completed cycles in a year is too low.

The SunAmp PCM storage has the advantage of having modularity, so that modules can be added or removed depending on the necessities, apart from enabling also the weight load distribution over the slab if necessary.

In the PCM storages design a parameter that must be defined is the Phase Change Temperature, this is the temperature at which the Phase Change Material changes its state storing the energy in form of latent energy. Thus the storage exchanges an important amount of thermal energy with a small temperature variation of the material around this defined temperature.

As mentioned in “1.2 Air source DC Heat Pump”, the whole system can be designed for two different heat demand ratios to be satisfied by the renewable system:

- Cover all or almost all the heat demand, what implies the DC heat pump being able to produce heat at the maximal required temperature by both the DHW and heating demand.
- Cover partially the heat demand by being the DC heat pump able to produce heat until a temperature lower than the maximal required and then the heat demand being completed by an auxiliary system.

This means three different options for the phase change temperature design of the PCM storage:

- A phase change temperature above the highest required temperature of both the DHW and heating demand. In this case the heat demand could be fully covered by the PCM storage if the stored capacity reaches the demanded energy.
- A phase change temperature lower than the maximal demand required temperature but greater than the return temperature of heating. In this case the PCM storage is able to deliver heat to the water main (for producing the DHW) in order to preheat it until the phase change temperature and also preheat the return from the heating until the phase change temperature. If one of the required temperatures for the DHW or heating demand is lower than the phase change temperature, then this demand could be fully covered by the PCM storage if the stored capacity reaches the demanded energy.
- A phase change temperature lower than the return temperature of the heating demand. In this case the PCM storage is only able to deliver heat to the water main in order to preheat it until the phase change temperature for producing the DHW. If the required temperature for the DHW demand is lower than the phase change temperature, then this demand could be fully covered by the PCM storage if the stored capacity reaches the demanded energy.

Other key properties of the phase change material to be selected are the heat storage density and the temperature range at which the latent heat exchange occurs. Greater heat storage density enable smaller volumes for the storage. This is important when the space for the storage is more reduced, but the price of the phase change material has to be also considered, so that a balance between the required space and the price has to be found. Regarding the temperature range for the latent heat exchange, it results more interesting the smallest range, thus the temperature level losses in the storage can be reduced.

Finally, the conductivity of the phase change material has also an influence over its performance, being more interesting those materials with higher conductivities.

In this way the DC Heat Pump operation is not mandatorily restricted to the moments and power of the heat demand. Thus, the heat pump can be more independently operated when the conditions for it are most favourable and the produced thermal energy is stored and after used when required by the heat demand.

Since the solar availability and the heat demand probably do not match in time and power shape, the use of this storage is necessary in order to disconnect the generation from the consumption. Furthermore, this storage enables also to optimize the installed power capacity of the generation system, since the capacity of the generation system does not need to cover the demand peaks.

1.4 Back-up system design

A Back-up system must be considered. Two use cases can be considered for the Back-up system exploitation during its design:

- Purely as a Back-up system, for those moments when the main renewable system here proposed is not able to work either due to the lack of solar energy which is the driving primary energy of the system, or due to maintenance works. Thus, the exploitation of the back-up system should be sporadic in the year.
- As an auxiliary system, complementing the base production of the renewable system here proposed in order to cover the peak demands or part of the demand that is not feasible to be covered by the main renewable system due to the high temperature required, or other kind of reasons, as the economic optimization or regulation limitations for the systems. In this case, the back-up system is quite often exploited.

If the Back-up system is designed for complementing the base heat production of the DC Heat Pump, then probably many moments it will be working simultaneously with the DC Heat Pump or the PCM storage delivery. Since the DC Heat Pump efficiency will probably be more affected by the inlet temperature than the auxiliary system and also the PCM storage is able to deliver heat until the defined temperature level, it is interesting to operate the back-up system in series: first the DC Heat Pump or PCM storage preheats the HTF increasing its temperature some degrees and finally the auxiliary system completes the heating process by increasing the HTF temperature until the desired temperature.

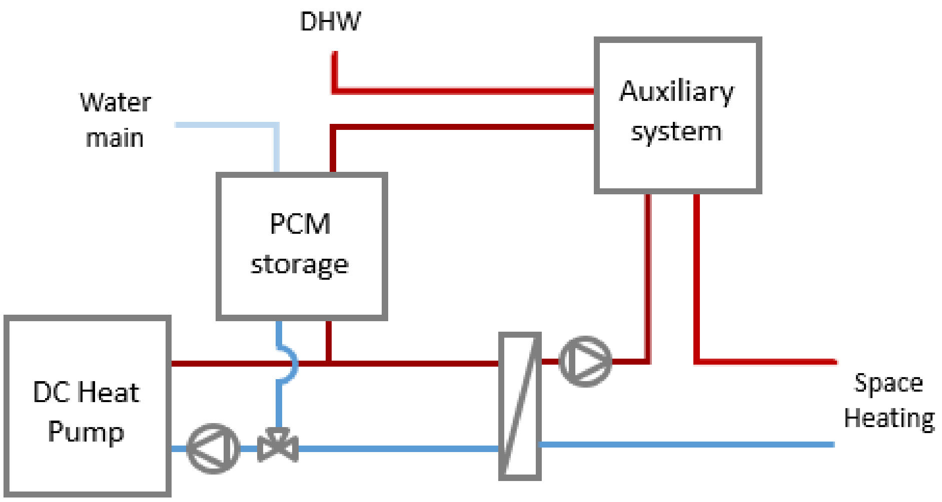


Figure 4. Scheme for the connection between the DC Heat Pump, the PCM storage and the auxiliary system.

In the retrofitting of an old thermal energy generation system with the new here proposed, it can be analysed if some of the already existing equipment could be used as Back-up system. This can be considered in the cases when the devices are still in good state and working fine and the reason for retrofitting the facility is in order to improve the system efficiency and get operation savings (in the economic, energetic and environmental aspects). If the retrofitting is promoted due to the fact that the existing equipment is obsolete and working deficiently or without satisfying the quality and security requirements, then they cannot be considered as Back-up system and must be replaced by new equipment. In this case, if new equipment has to be installed as Back-up system, it has to be taken into account that this equipment will have a low exploitation-capacity ratio, therefore it is more profitable a conventional system. Conventional systems have lower price-capacity ratio and thus lower investment costs but greater operation costs, and here the equipment is necessary to be exploited only part of the time but satisfying relatively great power demands.

Depending on the required temperature and the frequency of use, different conventional technologies can be considered for the auxiliary system. Thus, if the auxiliary system is going to be used occasionally and the required temperature is high (more than ~55 ºC) then a suitable system could be an electric heater. This is usually a cheap technology, with low price-capacity ratio, however its operation costs are great. If the auxiliary system is to be used more frequently, for example covering usually part of the demand and the required temperature is still high then a combustion boiler (gas or fuel) could be suitable. In case the auxiliary system is to be used also frequently, but the required temperature is not too high (until ~55 ºC) then an electric heat pump can be also considered. The suitability in this later case for the boiler or the heat pump depends on the energy prices (electricity, gas and fuel) as well as the average ambient temperatures, which influence the efficiency of the heat pump.

Table 1 summarizes the characteristics of the conventional heat production systems.

Technology	**Investment cost**	**Operation cost**	**Use**	**Reachable temperature**
Electric heater	Low	High	Occasional	> 90 ºC
Electric heat pump	Medium	Medium	Often	< 55 ºC
Combustion boiler	Medium	Medium	Often	> 90 ºC

Table 1. Comparative table for conventional heat production systems.

2 SYSTEM SIZING

The sizing of the system will depend on the characteristics of the case study, mainly on the heating thermal demand, the solar availability and the ambient temperature, and not disregarding the space availability for the equipment because it could restrict the size of some components of the facility.

One fact that has always to be considered when dealing with the sizing of renewable energy systems is that these ones have very low operation costs since they are driven mainly with renewable energy, but usually they have greater investment costs per capacity unit in comparison to the conventional systems. Thus, the costs are mainly the investment costs and depend on the installed capacity and the savings depend on the amount of renewable energy produced, what depends on the number of hours of exploitation of the installed capacity. Therefore when sizing a renewable energy system, in order to make it economically competitive and be able to obtain the greatest economic profitability and the lowest payback period, the goal is to minimize the installed capacity but maximizing the energy produced, what is achieved by maximizing the time of exploitation at a year. This is benefited by the use of storage systems or the combination with conventional systems to cover the peak loads, covering the renewable system a base and constant load.

In this case, furthermore, the storage system is neither a conventional system but an innovative one which presents better performance and storage density but also greater investment costs. Therefore, similarly to the renewable energy systems, it must be sized in order to maximize its exploitation, which in its case are the charge-discharge cycles at a year.

In this proposed system, the exploitation of the innovative systems will depend from one side on the heat demand and on the other hand on the available solar energy. Thus, the size of the DC Heat Pump must be defined so that it is highly exploited and this exploitation is not usually limited (in time and power) due to a relatively low demand or due to solar energy lack. Otherwise the unit would be oversized.

The development of a simulation model helps hugely to the sizing and operation optimization of these systems, since it enables to analyse which would be the performance of the system by changing different configuration on the size of the components as well as in their operation.

Following, some guidelines for the sizing of the different components of the system are given.

2.1 Solar PV system sizing

Solar field

The solar field has to be designed in order to be able to produce the daily required solar energy for driving the DC Heat Pump during the required hours of exploitation.

As usually done with the solar systems design, the orientation and slope of the collectors has to be optimized, taking into account also other possible limitations as potential shading elements or restrictions from national or municipality regulations, as could be the obligation of placing the collectors over the sloped roof keeping the same slope.

As a general rule and if the maximal yearly production is the goal, it can be considered that the optimal orientation is facing the equator (facing South in the North hemisphere and facing North in the South hemisphere), and the optimal slope is similar to the location latitude. Lower collector slopes than the latitude maximize the production in summer, while greater collector slopes maximize the production in winter.

Obviously, it has to be taken into account the amount of available solar surface as the potential maximal surface for the system.

In case the DC Heat Pump is to be supplied only by the DC electricity from the solar field, the sizing of the solar field has to be done in parallel to the sizing of the DC Heat Pump. Ideally, the DC Heat Pump is sized in order to produce the daily heat demand in the winter days, what implies a defined DC electricity which has to be provided by the solar system. However, if the solar field surface is restricted due to any reason, the DC Heat Pump has to be sized in relation to the daily available solar energy for its activation.

In case the DC Heat Pump is supplied by both the solar field and electricity from the grid, the solar field can be sized in order to maximize its profitability, taking into account the possibility of delivering the electricity surplus not used by the DC Heat Pump to the electrical grid obtaining some economic gains. Here it has to be taken into account the legal and economic conditions (regulations, price, tolls or incentives, etc.) for the electricity delivery from the solar system to the grid.

Probably, the solar field size obtained in a dimensioning for satisfying the required DC Heat Pump exploitation time is oversized during summer, since the heat demand in summer for DHW (and heating if existing) is lower and additionally the production of the solar system is also greater in summer. Thus, the solar PV electricity surplus should be delivered to the AC electrical grid of the building, being used in the building and reducing the consumption from the electricity supply or even selling electricity surplus to the electricity distributor if the building is not able to consume all of it.

A configuration issue when designing the solar field is the distribution of the panels in strings and number of panels in series. This depends on the number of connections and power of the inverter (integrating the MPP tracker) and the panels performance. It has to be considered that from the performance of the photovoltaic cells, there is an optimal voltage for the panel depending between others on the panel temperature, which in turn depends on the ambient conditions as radiation, ambient temperature, wind, etc. The optimal voltage varies however within a defined voltage range (~ ±20%) around the 0.5 V for one cell, thus the optimal voltage for one panel is around 0.5 times the number of cells of the panel. From other hand, the inverter is able to provide a voltage range, with a minimal and a maximal voltage, so that the maximal number of panels in a string is determined by the ratio between the maximal voltage of the inverter and that one of the panels. Thus, the number of solar panels in series should be defined.

Even if different strings connected to a same inverter comprise different number of panels or due to any reason (orientation, shadings) the radiation over the strings are different, the inverter itself is able to submit each panels string to its optimal voltage.

It should also be considered whether the extend of shading or requirement for multiple panel orientations and inclinations justifies the use of an inverter system with individual panel MPPT. The benefit can be determined by carrying out detailed simulations of the potential generation from the site using proprietary software comparing a string inverter system with a system equipped with power optimization. It should be noted that if a system with individual panel optimization is selected it makes uneconomic having delivery of both AC and DC power from the solar system.

This solar system should be also exploited during summer, when there is a lower heat demand for DHW or heating necessities. Therefore the PV solar production probably is greater than the required by the DC Heat Pump for satisfying the heat demand. In this case, the surplus generated electricity shall be delivered to the rest of the building and to the grid.

Finally, there are additional issues as in any solar PV system which are solved as typically for the solar PV systems: cables, DC electric box, AC electric box and the required monitoring sensors.

Solar inverter

For the sizing of the inverter capacity, it has to be taken into account that the inverters are characterised by its output power. Then, the required output capacity for the inverter is obtained from the radiation at the moment of the year with the maximal radiation over the panels surface, the panels efficiency, and the inverter efficiency. It has also to be taken into account that this moment of maximal radiation over the panels happens during a few hours in the year.

2.2 Air source DC Heat Pump sizing

As explained in the introduction of this section, it has to be considered when sizing renewable energy systems that they have very low operation costs but they have great investment costs per capacity unit in comparison to the conventional systems. The main costs are the investment ones which depend on the installed capacity, and the savings depend on the amount of renewable energy produced, what depends on the number of hours of exploitation of the installed capacity. Therefore, in order to make it economically competitive and get the lowest payback period, the goal is to maximize the exploitation time for the installed capacity at a year.

For this reason the DC heat pump must be dimensioned in order to be exploited as much as possible.

Here it has to be taken into account two limitation factors:

- The heat production temperature
- The electricity supply for the DC Heat Pump

As mentioned in "1.2 Air source DC Heat Pump", the system can be designed for two different heat demand ratios to be satisfied by the renewable system, depending on either the DC Heat Pump is able to reach the required temperature and cover almost all the heat demand or the DC Heat Pump is producing heat until a determined temperature level and the auxiliary system is responsible to complete the heat generation. In this way, the greater the heat production temperature of the DC Heat Pump the greater the ratio of demand that can be covered but the lower of the system efficiency, what hinders the unit profitability. Therefore a balance between energy produced and production efficiency must be found, defined by the desired payback-period.

Regarding the electricity supply for the Heat Pump, there are two options:

- Consider as power supply for the DC Heat Pump only the electricity from the PV panels
- Consider for the power supply of the DC Heat Pump also electricity from the grid, inverted through the AC/DC inverter

The second option is the more interesting one, since it enables a much greater exploitation of the DC Heat Pump in the year, what makes it more profitable reducing its payback-period and also facilitates its sizing.

Power supply from solar field and electricity grid

In this case, the ideal capacity of the Heat Pump should be that one able to produce during all the day the daily demanded energy, working together with the storage in order to store energy in the moments of lower demand and use it later in the moments of higher demand. However, the daily demand is not constant for all the days in the year but varies from day to day in a cycle at yearly scale, and furthermore being able to cover all the heat demand implies producing and storing at the required temperature level, which could imply the Heat Pump working with low efficiency. So that a greater installed capacity for the Heat Pump produces a greater amount of energy in a year, but has lower exploitation (in hours at 100% of capacity) and efficiency than a smaller installed capacity, which is so more profitable and has a lower payback-period. Thus, the investment costs increase almost linearly with the installed capacity, while the operation savings increase with the installed capacity, not proportionally but with a saturation curve. Therefore a balance must be found between the amount of energy produced and the payback-period.

In this case the sizing of the DC Heat Pump capacity does not depend from the solar field surface and capacity, since power supply can be done from the electric grid.

The final adjustment of the energy generation from the DC Heat Pump to the heat demand profile is done through the use of the storage and the combination with a back-up system for covering the greatest peak demands or higher temperature requirements if necessary.

Power supply only from solar field

In case the DC Heat Pump is only supplied by the PV solar energy then it requires the presence of two inputs for its exploitation:

- Solar radiation, converted to DC electricity through the PV panels and converter
- Heat demand or storage capacity at the PCM storage for storing the production

There are in this way two possible limitations for the DC Heat Pump sizing: the heating demand and the solar energy availability.

If there are no restrictions for the solar system and there is the possibility to produce as much solar energy as necessary, then the DC Heat Pump is designed depending on the preference for optimizing its profitability (defined by the payback-period) or the heat production. Then, the capacity of the DC Heat Pump will be determined from the balance between the heat energy produced and the payback-period.

However, if the solar system surface is restricted due to any reason, the DC Heat Pump has to be sized in relation to the daily available solar energy for its activation. Then, the capacity of the DC Heat Pump will be defined from the daily available solar energy.

DC Heat Pump in cooling mode

The DC Heat Pump is dimensioned for its heating mode. The use of the DC Heat Pump in cooling mode is an additional use for the equipment installed but should not define the device dimensioning.

Sizing of the heat exchangers for circuits separation

As explained previously in the design section, the use of heat exchangers can be required for the separation of the DC Heat Pump water circuit from the old heating emission systems circuits. The installation of these heat exchangers implies additional electrical consumption of the circulating pumps as well as the introduction of a temperature level lose between the temperature in the Heat Pump water circuit and the heating emission system, what implies worse temperature conditions for the unit performance, since the unit performance is quite sensible to the temperature at the condenser.

Therefore the heat exchangers must be dimensioned trying to minimize these disadvantages and a great heat exchange between the fluids with the smaller as possible temperature difference and the minimal introduction of pressure losses by the heat exchanger are desired.

A suitable solution for this case are the cross flow plate heat exchangers, which have a huge exchange surface in a compacted volume. The cross flow heat exchangers enable to get outlet temperatures in the primary circuit closed to the inlet temperature from the secondary circuit, which is the goal in our case in order to minimize the temperature level losses.

Of course, the investment costs and the available space have also to be taken into account. The ideal heat exchanger would have a great heat exchange with very low temperature differences between primary and secondary fluid, but such a device has a great cost. A balance must be found between the investment cost of the heat exchanger and the improvement in the Heat Pump performance and consequently in the operation costs.

2.3 PCM storage sizing

The storage volume must be determined accordingly to the time deviation between the heat generation and the heat demand. Since the heat production and the heat demand do not match in time and power shape, the use of this storage is necessary in order to disconnect the generation from the consumption. Furthermore, this storage enables also to optimize the installed power capacity of the generation system, since the capacity of the generation system does not need then to cover the demand peaks.

As indicated in the design section, this must be enough to store all the daily heat production from the DC Heat Pump but not a too much volume so that the number of complete cycles in a year is too low since this would mean it is oversized. A good exploitation reference could be a total yearly charged-discharged energy around 300 times the latent heat capacity, but this also depends on the price of the PCM.

On the other hand, a key parameter in the design of the PCM storage is the Phase Change temperature (and the width of the temperature range at which the latent heat exchange occurs). This determines the production temperature of the DC Heat Pump and thus its performance efficiency, as well as the ratio of the heat demand covered by the innovative system, i.e. the DC Heat Pump and the PCM storage.

For this reason, when studying the optimal storage capacity and calculating the thermal energy to be delivered from the storage to the demand it has to be taken into account the temperature level of this stored heat, since this delimits this amount of energy to be delivered by the PCM storage. The storage is in this way able to increase the HTF temperature until a temperature level which could be enough for covering the heat demand or only as a pre-heating of the HTF, being necessary the contribution from the auxiliary system to complete the HTF conditioning for satisfying the demand.

As mentioned in the design section, the whole system can be designed for different phase change temperatures in the design of the PCM storage:

- A phase change temperature above the highest required temperature of both the DHW and heating demand. In this case the heat demand could be fully covered by the PCM storage if the stored capacity reaches the demanded energy.
- A phase change temperature lower than the maximal demand required temperature but greater than the return temperature of heating. In this case the PCM storage is able to deliver heat to the water main (for producing the DHW) in order to preheat it until the phase change temperature and also preheat the return from the heating until the phase change temperature. If one of the required temperatures for the DHW or heating demand is lower than the phase change temperature, then this demand could be fully covered by the PCM storage if the stored capacity reaches the demanded energy.
- A phase change temperature lower than the return temperature of the heating demand. In this case the PCM storage is only able to deliver heat to the water main in order to preheat it until the phase change temperature for producing the DHW. If the required temperature for the DHW demand is lower than the phase change temperature, then this demand could be fully covered by the PCM storage if the stored capacity reaches the demanded energy.

A lower phase change temperature enables a lower production temperature for the DC Heat Pump and consequently greater efficiency but a lower demand ratio covered by the storage, while a higher phase change temperature implies a greater demand ratio covered by the innovative system. Therefore, a balance between the demand ratio covered and the DC Heat Pump efficiency must be found in order to get the optimal configuration either for an energetic or economic optimization, or a compromise between both. This could be defined by analyzing the simultaneous influence of both effects over the whole system pay-back period, and look for the maximal energy efficiency within a limit payback-period.

Here, transitory simulation model calculations are hugely helpful for determining the optimal phase change temperature and size of the storage.

Obviously, the storage volume is limited by the space availability as well as by the maximal admissible load of the slab where it has to be placed. If these conditions limit the PCM storage, then the capacity of the DC Heat Pump should be dimensioned accordingly to the maximal installable PCM storage. In any case, the PCM storage offers advantage in terms of store density in comparison to the conventional sensible thermal storages (generally water tanks), as well as the possibility of the weight load distribution over the slab thanks to its modularity.

2.4 Back-up system sizing

As mentioned in "*1.2 Air source DC Heat Pump*", the new proposed system can be designed for two different heat demand ratios to be satisfied by the renewable system, depending on either the DC Heat Pump is able to reach the required temperature and cover almost all the heat demand or the DC Heat Pump is producing heat only until a determined temperature level and the auxiliary system is responsible to complete the heat generation.

Depending on the use frequency for the auxiliary system and the required temperature and since the characteristics presented in Table 1 of section "*1.4 Back-up system design*", the conventional technology for the back-up system is chosen.

In any case, and independently of the use frequency of the back-up system, its capacity must be dimensioned for its appropriate performance in the worst case. The worst case is that one of greater demand for the Back-up system, and would happen when the innovative system is not able to produce heat due to any reason (no solar radiation available, stop for maintenance, etc.) and the indispensable heat demand is at its maximal power in the year, so that the capacity of the back-up system must be enough to satisfy this indispensable heat demand in this moment.

Even a combination of two different technologies could be considered for reaching this auxiliary power, if a capacity is going to be required usually for exploitation and an extra capacity is going to be required only sporadically.

3 OPERATION OPTIMIZATION

An optimal operation of the proposed system is necessary in order to maximize the benefits aimed with the facility retrofitting and the greater investment effort assumed with the proposed innovative system. One of the main barriers for the expected spread of some innovative technologies has been sometimes the bad experiences in the first installations due to a not optimized operation of the systems (usually they require a more complex operation than conventional systems and responsible personnel are not used to it), so that the operation savings have not been completely achieved and the investment effort has not been translated to the expected benefits, what has disseminate a bad general opinion about these systems. Therefore it is crucial to operate these innovative systems correctly and in an optimized way in order to achieve the greatest benefits and make profitable the greater investment effort.

For determining the optimal operation, it will depend on either the supply for the DC Heat Pump is only from the PV panels or if also from the electrical grid.

The ideal operation is that one with which the daily demand is satisfied with the minimum energy consumption. In order to get this, the heat production should be realized with the maximal efficiency.

Simplifying a little bit the complexity of the system, the key for the heat pump efficiency lays in the temperature difference between the ambient and the production temperature. Thus, producing the heat at the moments when the demand occurs (mainly during the morning and night) implies a determined temperature difference (DT) between the ambient and the heat pump production. Considering that producing this heat to be stored would imply to produce it at a higher temperature, e.g. 5 degrees, this means that the heat pump would produce during the central hours of the day this amount of heat required in the morning/night to be stored (5 degrees higher) with the same or better efficiency if the ambient temperature is 5 or more degrees higher (and furthermore more DC electricity from PV panels is available).

Additionally, it has to be taken into account that the required temperature by the Space Heating demand depends on the external temperature through a climatic curve, and also that the self-produced PV electricity probably has greater value if consumed at the building (avoiding consumption from the main electricity grid) than if delivered to the main electricity grid.

The total daily amount of heat demanded must be produced then in the moments when the DT between the heat pump sources are going to be the lowest, taking into account the instantaneous power demand and thus if the produced heat is to be sent to the demand or to be stored, what determines its required temperature. Always taking into account that the electricity from the PV panels should be consumed inside the building. If there is PV electricity surplus, then probably has sense to use it to produce and store heat at the PCM storage instead of delivering it to the main electric grid.

It has to be found the optimal distribution of heat production between the central hours of the day and the hours of more demand so that the system efficiency during its operation is maximized.

Therefore within the proposed HEAT4COOL system a heuristic rule-based controller (HRBC) together with a deterministic model predictive controller (MPC) has been developed [1].The MPC algorithm exploits forecasts of weather, apartment temperature set-points, occupancy profiles and energy prices to estimate the best operation of the proposed heating system from an economic standpoint of view. Figure 5 shows the scheme of the HRBC and MPC controllers communication and their data flow.

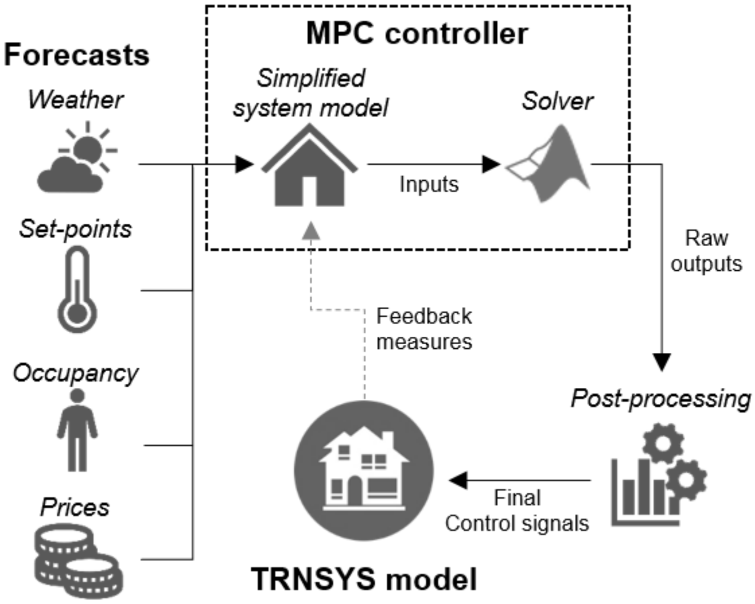


Figure 5. Scheme of the control system composed by the HRBC and MPC controllers [1].

If the heat pump is to be supplied only by the PV panels, then the operation is simplified by trying to concentrate the heat production on the central hours of the day, and extending this exploitation to the contiguous hours (with the available DC power from PV panels) in order to produce the required daily heat demand.

Regarding the PV solar system, the optimized operation of the panels consists simply in produce the maximal PV energy as possible from the available radiation, what is controlled by the MPP trackers.

4 ACRONYMS AND TERMS

AC .... Alternating Current

PV................................ Photovoltaic

DC .... Direct Current

PCM .... Phase Change material

MPPT .... Maximal Power Point Track

DHW .... Domestic Hot Water

HTF .... Heat Transfer Fluid

DT................................ Temperature Difference

HRBC.......................... Heuristic Rule Based Controller

MPC .... Model Predictive Controller

5 REFERENCES

[1] E. Zanetti, R. Scoccia, M. Aprile , M. Motta, L. Mazzarella, M. Zaglio, J. Pluta. *Building hvac retrofitting using a pv assisted dc heat pump coupled with a pcm heat battery and optimal control algorithm*. Paper at: CLIMA2019 REHVA 13th HVAC World Congres, 26th-29th May Bucharest (Romania) 2019.