Mathematical Modelling of Power to heat Strategies to support Sector Coupling

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Abstract

Sector coupling refers to the idea of interconnecting the energy consuming sectors like buildings (heating and cooling), mobility, gas and industry with the electricity-producing sector. Among several sector coupling strategies, power to heat (P2H) poses as one of the most necessary ones, since heating and cooling accounts for 51% of the final energy demand in the world, and only 10% of it is provided by renewable sources (REN21, 2019). In this work, different P2H systems and applications, namely a residential and an industrial application were investigated and the total energy produced by them was stored in water tanks for a later on use. Based on those results, it could be determined which one of the systems analyzed provided the best solution in terms of energy conversion in comparison with each other. Furthermore, in order to provide a general idea of the greenhouse gas emissions avoided, the amount of CO_2 and fossil fuel savings was computed and presented in the results section. The mathematical modelling of the all systems was created using MATLAB/Simulink^{TM}, and their results are displayed in this work.

Keywords: Power to heat, Sector coupling, Mathematical modelling

1. Introduction

Power to heat (P2H) technologies have proven themselves as a reliable ally when it comes to balance the energy grid and promote the use of the surplus energy produced by the renewable systems during peak moments. As it is well known, among several advantages, one of the principal ones is the ability of providing grid stabilization by shaving the peak energy and supporting the balance of the asymmetric load. This is done by avoiding the shutdown of solar power stations or wind turbines during grid overload moments and using this extra energy to run the P2H systems, which will then, convert this electrical energy into heat.

When considering the implementation of a renewable energy power plant it is important to consider, not only the amount of energy that can be produced by it, but also the amount of CO_2 emissions that can be avoided. It is notorious that the carbon dioxide and other greenhouse gases emissions are responsible for the increase in the planet's temperature by nearly 1°C since the Industrial revolution, and that those gases come mainly from human activity. That is the reason why in the last decade, several climate policies to reduce these emissions were developed and why several subsidies were created for the construction and implementation of renewable power plants all over the world (Ritchie, Rosesr, 2017).

Based on those subsidies, in the last few years, the installation of clean renewable electrical energy and heat generation systems became progressively accessible not only to the average homeowners but also for the industries. This has a positive impact because in most developing countries the industries accounts for more than a third of total final energy consumption, and up to eighty percent of this sector's energy is used to produce heat (process heat for high or low temperature applications). Therefore, there is an increasing necessity for the industries to make use of cleaner sources of electricity and heat (Wohlgemuth, Monga, 2008).

In this work, different ways of implementing power to heat systems were analyzed, namely a residential and an industrial application, and simulations were performed using the software MATLAB/Simulink ^{TM}. One of the goals of this work is to evaluate the amount of energy that can be produced by the systems and which quantity of it can be converted into heat and stored in a water tank, fulfilling this way the integration concept of the sector coupling. A second objective is to determine which one of the systems analyzed provide the best solution in terms of energy conversion in comparison with each other, as well as avoided fossil fuel use and avoided CO_2 emissions to the environment.

doi:10.18086/eurosun.2020.05.09 Available at http://proceedings.ises.org

2. Methodology

In order to provide a comprehensive investigation about the power to heat implementation possibilities, two types of applications were compared. As previously mentioned, the first type was a residential application and the second type an industrial application. It is important to note that all the systems used in the simulations here performed were extracted from the CARNOT block-set in MATLAB (Solar Institut Juelich, 2018) and some of them were modified according to the goals of the project. In the following sections, the structure, major components and configuration of each of these systems will be presented, in parenthesis, next to the name of each component, one can find the corresponding name of the Simulink block in the CARNOT block-set.

2.1. Residential application

For this application, the domestic hot water generation for a single-family house was examined and a comparison between a conventional solar thermal system and a power to heat strategy was investigated. For both systems, it was considered that three people lived in the house and that the amount of water used per person was around 50 liters (l) per day, totalizing a Domestic Hot Water (DHW) use of 150 l of per day. With the purpose of meeting these criteria, a water tank containing 400 l of water was used as storage system and a water taping scheme was created to regulate the consumption behavior of the household. Concerning the tapping system, it was developed to tap the water from the tank three times per day, namely at 7:00, 13:00 and 19:00 o'clock, with the tapping in the morning and in the evening lasting twice as long as the tapping at noon and all of them summing up 150 l of water by the end of the day. In the next sections, the characteristics of both systems will be discussed.

2.1.1. Photovoltaic system plus electric heater

Regarding the P2H system, the approach considered was a photovoltaic system plus an electric heater. The basic components used in this simulation were photovoltaic panels (PV) with 4.2 kWp power *(PV Module simple)*, an electric element *(Electric Heating)* and a water storage tank *(Storage Type 2)* containing 400 l of water. In this arrangement, the PV was used to provide electricity to the electric element that was immersed in the water storage tank and installed in a height equivalent to 25% of the tank total height, counting from the bottom to the top. Regarding the tank, it is arranged in a standing position and starts with a temperature of 65 ºC.

For backup purposes, an additional electric element system was installed in the tank (at around 70% of the tank total height), this being powered by the grid energy.

2.1.2. Solar thermal collectors plus water storage tank

As it is well known, the solar thermal water system is not part of the power to heat systems category, nevertheless, it was here included in order to provide a source of reference to the study. The basic components used for this system were a water storage tank *(Storage Type 2)*, with the same characteristics as the previous one (400 l and initial temperature of 65 ºC) and a solar thermal collector system (ST) *(Solar Thermal Collector ISO 9806)*, which is directly connected to the tank. For auxiliary purposes, a water pump *(Pump Constant)* was also included, which pumps the water from the tank back to the solar collector. In order to keep all the systems comparable, a thermal collector size of 6 m² was chosen. Using the well-established conversion factor of 0.7 kW/m² (Weiss, Spörk-Dür, 2019), this corresponds to an output power of 4.2 kW_{th}, equal to the PV system mentioned above, which presents an area of about 28 m², (assuming an efficiency of 15%).

Alike the previous system, in this arrangement, for backup purposes, an additional electric element system *(Electric Heating)* was installed inside of the tank (at around 70% of the tank total height), this also being powered by the grid energy.

2.2. Industrial application

For this application, the generation of hot water for any industrial demand was analyzed and a comparison between two distinct power to heat strategies was investigated. For both systems, a water storage tank with 50 m^3 was used and the goal was to keep water temperatures between 60 ºC and 95 ºC inside of the tank during the whole year. As well as in the previous application, a water use profile was also developed for this arrangement, but in this case, instead of tapping water only three times during the day, the water was constantly drawn from the tank between 7:00 and 17:00 o'clock and used in the industry processes. Considering that, a constant amount of 100 kW was constantly being drawn from the tank, after the ten hours of operation a total of 1000 kWh was consumed per day in this system. The characteristics of both systems are discussed below.

2.2.1. Photovoltaic plus electric heater

The basic components used in this simulation were photovoltaic panels (PV) *(PV Module simple)* with 200 kWp output power, an electric element *(Electric Heating)* and a water storage tank *(Storage Type 2)* containing 50 m^3 of water. In this arrangement, the PV was, again, used to provide electricity to the electric element that was immersed in the water storage tank and installed in a height equivalent to 25% of the tank total height, counting from the bottom to the top. Essentially, this system is a scaled up version of the photovoltaic system used previously for the residential application.

This design also presents an electric element installed in the upper part of the water tank, working as a backup heater.

2.2.2. Photovoltaic plus heat pump

The basic components included in this arrangement were a water/water heat pump with 200 kW electric power, a photovoltaic system and a water storage tank. For the sake of comparability, the same photovoltaic system *(PV Module simple)* with 200 kWp power and water tank *(Storage Type 2)* with 50 m^3 of water, stating at 65 °C, used in the previous system, were implemented in this arrangement. Water pumps *(Pump Constant)* and an inverter *(Inverter)* were also included in order to complete the connections between the main components. An electric element *(Electric Heating)* was also installed in the upper part of the tank to operate as a backup heating system. In this system, the PV system is used to provide energy to the heat pump, which transfers heat to the water tank, additionally, the temperature of the water coming from the ground heat source to the heat pump is always around 10 °C.

3. Simulation Results

3.1. Residential application results

This section aims to compare the pure thermal system described in Section 2.1.2, with the system using a power to heat strategy described in Section 2.1.1. In order to provide a broader view of the systems functionality, an annual and a daily comparison of both systems was performed. It is also important to notice that, the weather files used for all simulations here performed, come from a region in West Germany.

Daily comparison: For this comparison, two different days with distinct weather conditions, one in summer and the other in winter were chosen and the water temperature obtained throughout the tank was measured. In order to allow a better observation of the temperatures inside of the water tank, the same was divided into ten nodes being Node 1 on the very bottom and Node 10 on the top, which can be seen on the top part of the Figure 1 and Figure 2 below.

Since, for the photovoltaic plus electric heater system, the heating element was installed in the second node, it is possible to observe that when the water tapping occurs, the temperature on the bottom of the tank decreases, while the temperature for the other nodes do not change so much. This happens due to the difference in density between hot and cold water, as it is known, hot water has a smaller density than the cold water and is carried to the upper parts of the tank. At the end of the day, a bigger difference between the layers can be noticed, with the bottom layers colder than the top ones.

Regarding the solar thermal system, the heat exchange zone between the solar collector and the water tank is located in the bottom of the tank and therefore, a similar behavior as in the previous system can be detected. In this arrangement, it is also possible to notice that when the tapping occurs, the temperature of water inside the tank starts to change and at the end of the day, a greater difference between the layers can be seen.

It is also important to highlight that a temperature limit of 95 °C was set in tank in order to avoid water temperatures higher than 100 °C. Consequently, during some days with high solar radiation (normally in summer) when the water temperature in the tank reaches the limit, no more energy is transferred from the photovoltaic or solar thermal system into the tank.

Figure 1 and Figure 2 display the behavior presented during a sunny summer day. In this case, the solar thermal and the photovoltaic system present similar results, nevertheless, one can notice that between the first and second tapping, in the photovoltaic system the temperatures between the different nodes is basically the same, while in the solar thermal system there is already a small variation amid the temperatures.

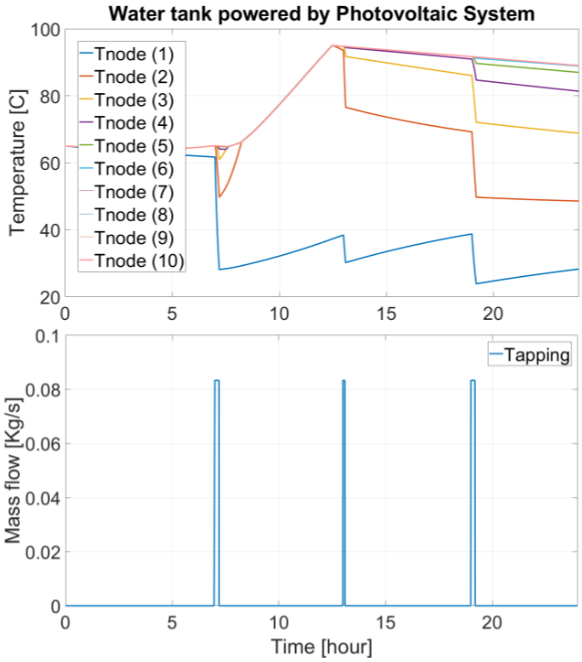

Figure 1: Final temperature in water tank with PV system (top) and tapping mass flow (bottom) in a summer day

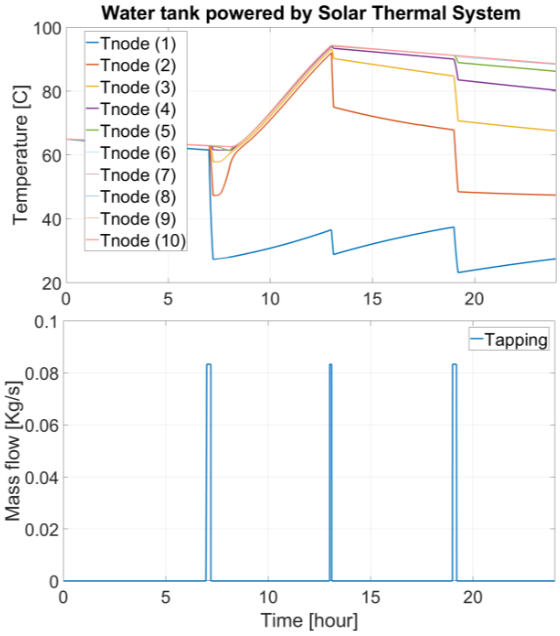

Figure 2: Final temperature in water tank with ST system (top) and tapping mass flow (bottom) in a summer day

With respect to the winter day, Figure 3 and Figure 4 display how the systems behave with such weather conditions. For the photovoltaic arrangement, it is possible to see that in the middle of the day the temperature in the middle nodes of the tank increase a bit and that at around 19:00 o'clock, when the last tapping occurs, the last node increases its temperature suddenly, which happens because the backup electric heater started to function. As formerly explained, a backup heater was installed in the upper part of the tank in all systems and it was set to start operation when the water temperature around it decreased below 60 °C.

Concerning the solar thermal system, the temperature in the tank decreases throughout the day and at 16:00 and 19:00 o'clock it is possible to see an increase in the temperature of the top nodes, which again happens because the backup heater started to function, when the temperature reached levels below 60 °C.

By the end of this day, the PV system could provide almost 60 % of the energy needed to maintain the tank temperature at 60 °C, while the ST system did not deliver any energy to tank and had to use the backup heater, with energy coming from the grid. The reason behind this behavior is that, in a day with low irradiation or an overcasted day, the PV system can still produce a certain amount of energy to power up the electric heater, while, for the ST system, the amount of irradiation available is not enough to achieve high temperatures in the collectors, which therefore do not deliver any energy to the tank requiring then, the backup heater.

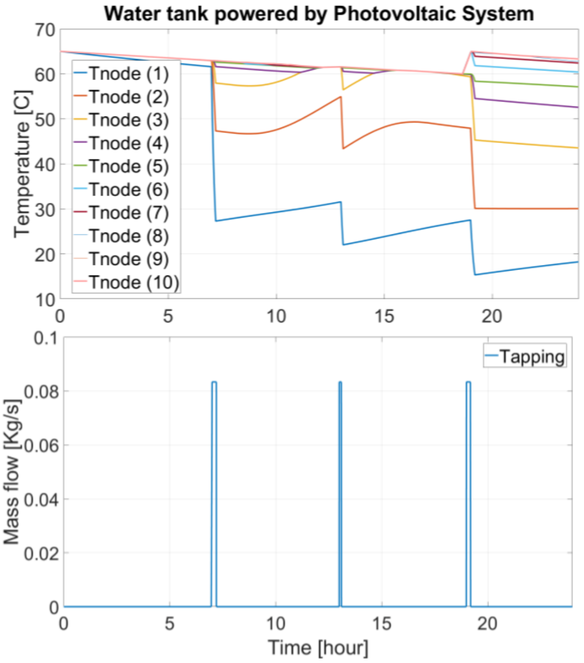

Figure 3: Final temperature in water tank with PV system (top) and tapping mass flow (bottom) in a winter day

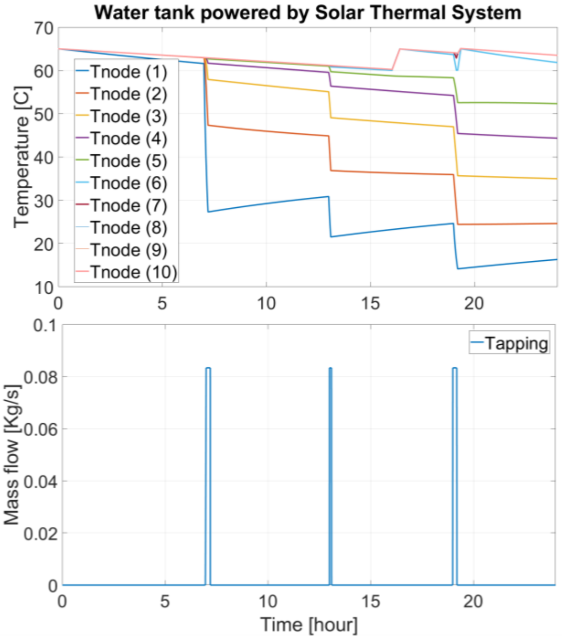

Figure 4: Final temperature in water tank with PV system (top) and tapping mass flow (bottom) in a winter day

Annual comparison: For this comparison, the annual behavior of both systems was analyzed. Here the focus was to calculate the total solar fraction supplied by the systems and also the avoided fossil fuel use and the avoided CO_2 emissions.

Figure 5 and Figure 6 display the total annual amount of energy produced by the solar thermal and the photovoltaic system, respectively, as well as the amount of energy needed from the grid during the year. One can perceive that in Figure 5, the final difference between the grid consumption and the ST system production is smaller than the difference between the PV system production and the grid consumption displayed in Figure 6. This indicates that the photovoltaic system needed less energy coming from the grid during the year than the solar thermal arrangement. In both pictures, during the periods with better weather conditions, from around day 100 till day 300 (sunnier days with reduced amount of clouds), it is possible to observe that the Grid need slightly increase in the ST simulation, while for the PV system, the energy needed from the grid basically does not change during this time. Therefore, during this time the photovoltaic system was able to provide all the energy needed to keep the temperature inside the water tank at the desired levels without using any backup power coming from the grid. While, on the other hand, the solar thermal system needed some backup coming from the grid.

- Solar fraction

Regarding the solar fraction, the total amount of energy needed to keep the water tank at the desired temperature was computed and the percentage coming from the grid and from the heating system was calculated. As it was expected, the photovoltaic system performed better and presented a higher solar fraction than the solar thermal arrangement.

For the solar thermal system, the solar fraction represents 66.5 % coming from the collectors and 33.5 % of the total energy coming from the grid. While for the photovoltaic system, 80.9 % from the total energy was provided by the PV panels, while only 19.1 % of the energy had to be consumed from the grid.

- Avoided fossil fuel use and CO_2 emissions

In order to calculate the amount of CO_2 equivalent of the technologies here presented, a report from energy and environmental research published by the government of Austria, which is based on the European Network Transmission System Operator for Electricity (ENTSO-E), was used as reference (Biermayr et al., 2020). Based on the total production of the solar thermal system per year, which was 2160 kWh and using the CO_2 equivalent emission coefficient of 434.7 gCO_{2equi}/kWh, it was possible to determine that the amount of 939 kilograms of CO_2 were spared by the use of this system. This is also equivalent to CO_2 emissions from 355 liters of diesel that could be spared by the use of this technology (Valsecchi et al., 2009).

With respect to the photovoltaic system, the annual production was around 2800 kWh, based on this value and using the same reference previously employed, the amount of CO_2 emissions avoided was determined as 1217 kilograms of CO_2 (Biermayr et al., 2020). This is also equivalent to CO_2 emissions from 460 liters of diesel that could be spared (Valsecchi et al., 2009). It is important to notice that this section focus on the CO_2 emission that could be spared by the use of the technologies here described and that do not take into account the CO_2 emissions during the manufacturing and recycling processes.

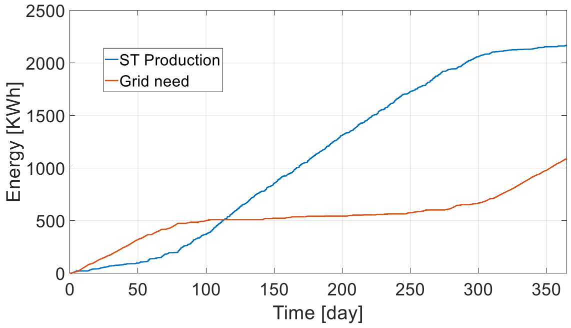

Figure 5: Yearly solar thermal energy production versus energy needed from grid

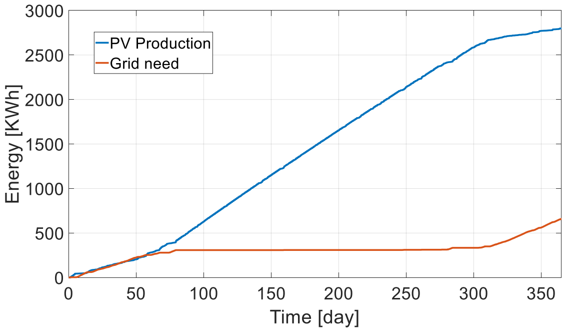

Figure 6: Yearly photovoltaic energy production versus energy needed from grid

3.2. Industrial application results

This section aims to compare the applications of the two different power to heat strategies discussed in sections 2.2.1 and 2.2.2, a photovoltaic system connected to an electric element and a photovoltaic system connected to a heat pump, respectively. The same strategy used for the residential application was also implemented for the industrial application, hence, in order to provide a broader view of the systems functionality, a daily and an annual comparison of both systems was performed. It is also important to notice that, the same weather files, from a region in West Germany, formerly used in the simulations, were also implemented here. Both systems have the purpose of keeping the water tank at the desired temperature in order for it, to be able to provide enough hot water to run distinct industrial processes.

Daily comparison: For this comparison, once more, two different days with distinct weather conditions, one in summer and the other in winter were chosen and the water temperature obtained throughout the tank was measured. For the industrial application, as well as in the previous application, in order to allow a better observation of the temperatures inside of the water tank, the same was divided into ten nodes, being Node 1 on the bottom and Node 10 on the top, which can be seen on the top part of the Figure 7 and Figure 8 below.

It is also important to emphasize that, also for this application, a temperature limit of 95 °C was set in the tank in order to avoid water temperatures higher than 100 °C. Therefore, during some days with high solar radiation when the water temperature in the tank reaches the limit, no more energy is transferred from the photovoltaic or heat pump system into the tank.

In Figure 7, it is possible to see the difference between the node temperatures as soon as the tapping starts and the PV system starts delivering energy to tank. As earlier mentioned, the photovoltaic system presents an electric element installed in the bottom of the storage tank, consequently, the temperatures from the second node upwards increase and the temperature of the bottom node continues to decrease. One can also notice that immediately after the tapping ceases, the temperatures inside the storage stop changing and remain the same until the end of the day.

Regarding the heat pump system, the heat exchange zone was installed on the bottom of the tank and when the heat pump operates all the nodes above the heating zone have their temperature increased as well. Across the day, the heat pump is turned on and off a few times, which leads to this peak behavior that can be observed in Figure 8. Also in this system, when the tapping stops, the temperature inside of the tank do not change anymore and remain the same until the end of the day.

When comparing both figures one can recognize that for the heat pump system the water temperature inside of the water tank reaches higher values than the ones achieved in the photovoltaic plus electric heater arrangement. However, in Figure 7, all the energy used could be provided by the system, while in Figure 8, part of the energy had to be provided by the grid, in order to power up the heat pump.

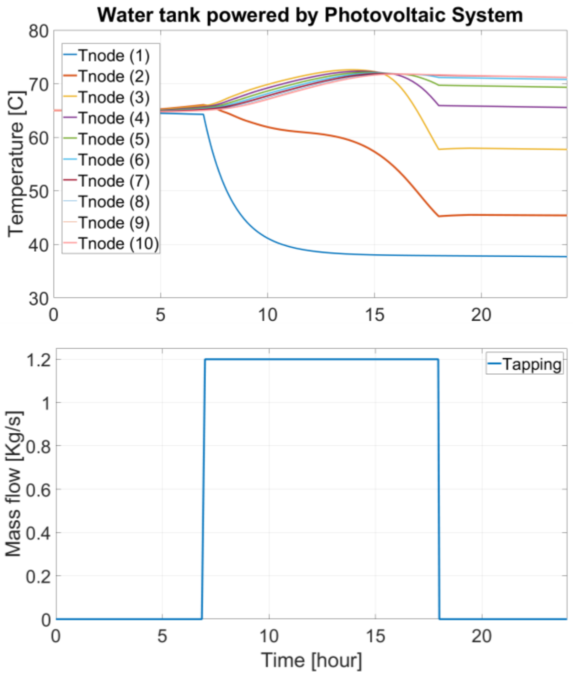

Figure 7: Final temperature in water tank with PV system (top) and tapping mass flow (bottom) in a summer day

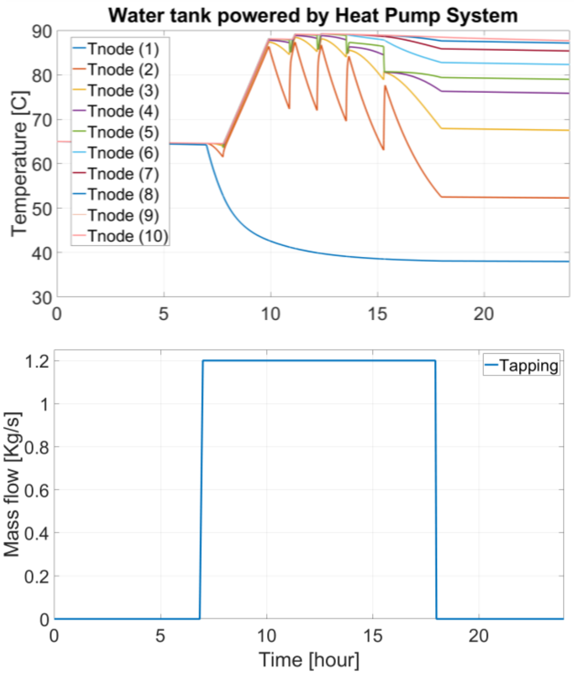

Figure 8: Final temperature in water tank with HP system (top) and tapping mass flow (bottom) in a summer day

Regarding the winter day, as earlier mentioned, in the photovoltaic system, a backup heating element was installed in the upper part of the tank, and should start operating when the temperature around it reaches values below 60 °C. Figure 9 presents the behavior of the photovoltaic arrangement in this day, and it is possible to observe that throughout this time, the temperature in the bottom layers of the tank decrease when the tapping begins. However, as soon as the temperature around the backup heater sensor reaches the set value (60°C), it starts operating and the temperature in the upper nodes increase.

With respect to the heat pump system, Figure 10 displays its performance in this winter day. It is possible to recognize the similarity between the peak behavior presented here and in Figure 8. In the winter day, however, the heat pump is turned on and off more often and the temperatures reached by the system are lower than the ones reached during summer, which was already expected. Once more, when the tapping in the system ceases the temperature of all nodes inside of the tank remain the same until the end of the day.

When comparing both systems, it is possible to notice that, the end temperatures inside of the tank differ considerably by the end of the day, in Figure 9 one can see that basically half of the tank has temperatures between 40 °C and 50°C, while in Figure 10, only the bottom node presents a lower temperature and all the other nodes have temperatures greater than 58 °C. Despite that, in order to keep the temperature at the desired level (60°C) both of them needed to consume energy from the grid. As predicted, the amount consumed was much bigger for the photovoltaic plus electric element arrangement than for the heat pump system.

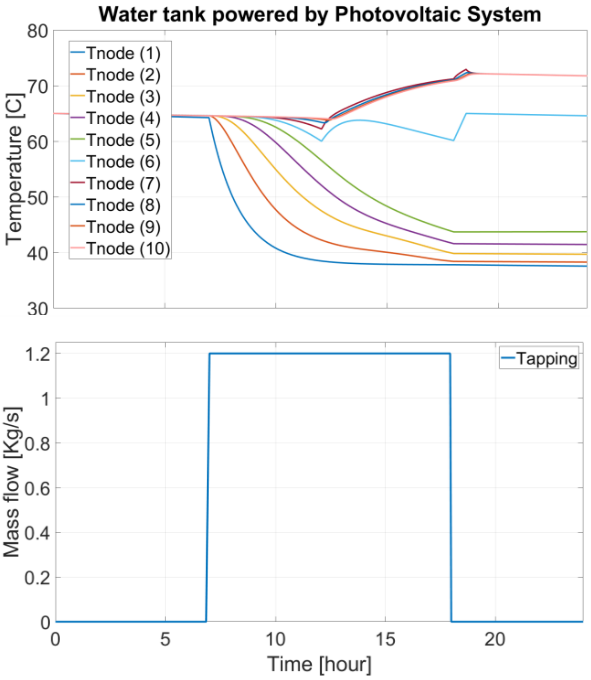

Figure 9: Final temperature in water tank with PV system (top) and tapping mass flow (bottom) in a winter day

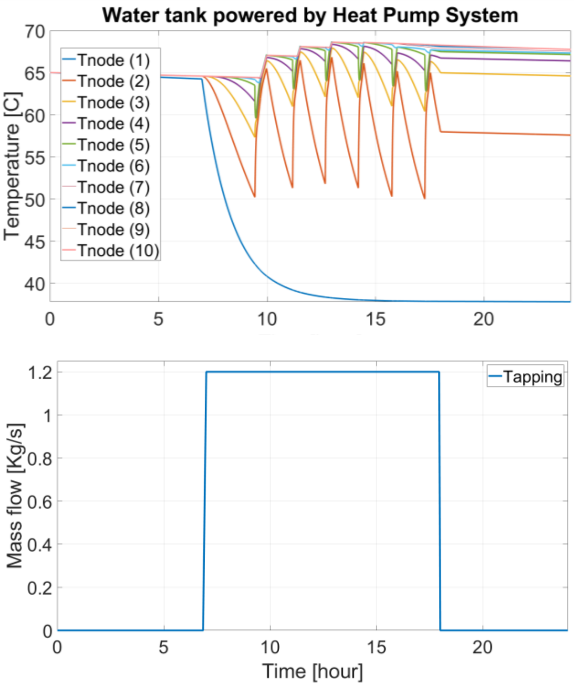

Figure 10: Final temperature in water tank with PV system (top) and tapping mass flow (bottom) in a winter day

Annual comparison: For both systems, it was observed if it was possible to maintain the desired temperature inside of the tank during the time while the tapping was occurring and how much extra power coming from the grid would need to be consumed to reach this goal in a yearly perspective. This section also focused on calculating the total renewable fraction supplied by the systems and also the avoided fossil fuel use and the avoided CO_2 emissions.

In Figure 11, the total amount of energy produced by the photovoltaic system to power the electric element during an entire year can be observed, as well as the total energy consumed from the grid in the same period. It can be noticed that, from around day 100 until day 300 (usually, sunnier days with reduced amount of clouds), the amount of Grid need (red line), present a small increase when compared to the periods in the begin and end of the year (winter days, usually with lower solar irradiation). Nevertheless, by the end of the year, the total amount needed from the grid was higher than what could be provided by the PV system.

Regarding the heat pump system, Figure 12 displays the total amount of energy consumed from the grid (red line) and the amount of energy provided by the renewable sources (photovoltaic plus heat source) to the tank. One can notice that this S shape behavior present in the previous picture during the summer months, for the grid energy, cannot be seen in Figure 12. This means that during this time, a higher amount of energy from the grid was consumed to power up the heat pump system than what was needed to power the electric element inside of the tank in the previous system.

When comparing both figures, it is possible to notice that the final amount of energy needed from the grid is far larger for the PV plus electric element system (232 MWh) than what is needed for the photovoltaic plus heat pump system (124 MWh). This happens due to the extra heat source energy that comes from the ground and is used as heat source by the heat pump, decreasing the amount of energy that this system needs to consume from the grid to keep the temperature inside the storage at the desired level.

- Renewable fraction

The renewable fraction corresponds, in this case, to the amount of energy that is being provided by the renewable sources in the systems here presented (photovoltaic and ground source). Not only for the photovoltaic plus electric element system, but also for the photovoltaic plus heat pump arrangement, the total amount of energy needed to keep the water tank at the desired temperature, was computed and the percentage coming from the grid and from the heating system was calculated. Concerning the industrial application, the photovoltaic plus heat pump system had a better performance than the photovoltaic plus electric element system and, therefore, presents a higher solar fraction.

For the PV plus electric element system, the solar fraction represents 45.7 % coming from the PV panels and 54.3% of the total energy coming from the grid. While for the PV plus heat pump system, 71.6 % from the total energy was provided by the PV panels and ground source, while 28.4 % of the energy had to be consumed from the grid.

- Avoided fossil fuel and CO2 emission

Based on the total production of the photovoltaic plus electric system per year, which was 196.2 MWh and using once more the CO_2 equivalent emission coefficient of 434.7 gCO_{2equi}/kWh, it was possible to determine that the amount of 83.5 tons of CO_2 were spared by the use of this system (Biermayr et al., 2020). This is also equivalent to the CO_2 emissions from 32 cubic meters of diesel (Valsecchi et al., 2009).

With respect to the PV plus heat pump system, the total annual production was 313 MWh, based on this value and using the same CO_2 equivalent emission coefficient of 434.7 gCO_{2equi}/kWh, it could be determined that the amount of CO_2 emissions avoided was 136 tons of CO_2 (Biermayr et al., 2020). This is equivalent to the CO_2 emissions from 51.5 cubic meters of diesel that could be spared (Valsecchi et al., 2009). As mentioned in the previous section, the focus of this investigation, is on the CO_2 emission that could be spared by the use of the technologies here described and do not take into account the CO_2 emissions during the manufacturing and recycling processes of these components.

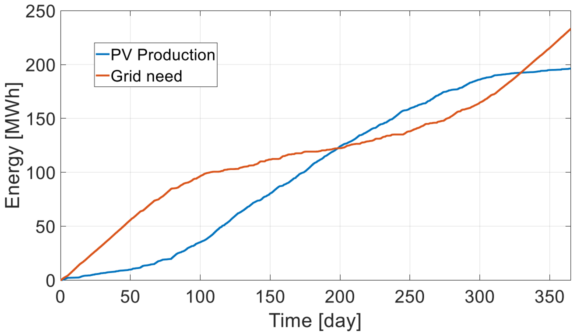

Figure 11: Yearly large scale photovoltaic energy production versus energy needed from grid

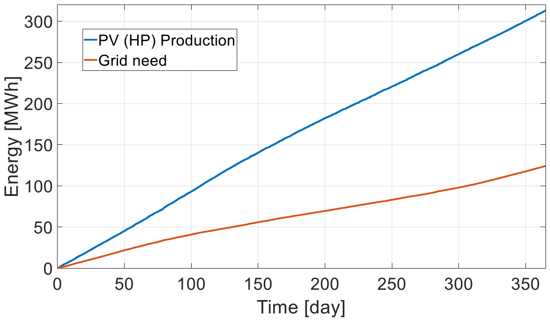

Figure 12: Yearly large scale photovoltaic energy production to heat pump versus energy needed from grid

4. Conclusions

In conclusion, this work could demonstrate that, first, the modelling of Power to Heat systems can be done utilizing MATLAB/Simulink ™ and that its results look reliable. Second, the models developed can be used not only for residential applications, but also in an industrial scale.

As previously discussed, one of the major goals of this work was to analyze different applications of P2H technologies and state if they are reasonable systems to be implemented in a sector coupling project. By the end of this study, it is clear that when it comes to integrate the energy coming from the renewable sources into the storage systems, all the different applications here proposed, presented a good outcome and that the bigger part of the energy generated could be incorporated into the storage systems. However, it was also possible to notice that some systems performed better than others did.

Regarding the household application, the solar thermal and the photovoltaic systems presented a satisfactory solar fraction when considering the annual simulation, having the photovoltaic arrangement a better performance (80.9% solar fraction) than the solar thermal structure (66.5%). This suggests that, both systems can be installed in a household with no further problems and that the habitants would have enough Domestic Hot Water throughout the year at the desired temperature.

Concerning the industrial application, it could be observed that the photovoltaic plus heat pump and the photovoltaic plus electric element systems showed a good performance. However, as it was expected, the solar fraction achieved in the annual simulation by the PV plus heat pump system was better (71.6%) than the one of the PV plus electric element arrangement (45.7%). Based on that it is possible to affirm that the photovoltaic system connected to the electric element immersed in the water tank not only performed better in the residential application, but also presented satisfactory results the industrial application and should definitely, be taken into consideration when considering a P2H strategy for a Sector Coupling project.

It also should be noted that, the use of any of the applications here discussed leads to CO_2 emissions savings and that, as previously presented, up to 136 tons of CO_2 could be spared, when using, for example, the PV plus heat pump system in the industrial application. This is important because these are times when, not only the CO_2 emissions of all energy systems should be taken in consideration but also how much fossil fuel use can be avoided by its implementation.

Factors like solar collector prices, photovoltaic panels' prices and investment capital for an eventual renovation of the heating system in the household or in the hot water cycle in an industrial plant can make one system be a better investment than the other but these were topics not explored in this work.

Finally, it is also important to remark that the weather file used in the simulations has a huge influence in the final results of the systems. In this work, as previously mentioned, the weather files used come from a location in West Germany, which presents a high amount of overcasted days throughout the year, which, therefore, decreases the amount of energy that can be delivered not only by the solar thermal system but also by the photovoltaic system. Choosing a location on the southern hemisphere or in places with a higher amount of sunny days throughout the year will lead to a higher solar fraction for all the systems here discussed and therefore a better performance.

5. Acknowledgments

This project is financed by research subsidies granted by the government of Upper Austria.

6. References

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