# Project report

## ADEPT planning – review and monitoring of energy technologies

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# 1 Executive Summary

Cranfield University has undertaken the analysis of the performance of innovative materials and systems to harvest renewable energy on behalf of Central Bedfordshire Council (CBC).

There were three systems that were trialled as part of the Association of Directors of Environment, Economy, Planning and Transport's (ADEPT), supported by Department for Transport (DfT), SMART Places Live Labs competition in 2019. The demonstration sites will encompass three types of energy generation: thermal (Power Road®), Kinetic (Pavegen®), and solar (WattWay®). The performance, costs and benefits of these technologies are evaluated in terms of economic and environmental aspects. Given significant differences in these three systems, types of data collected, and subsequent analysis carried out are different. Consequently, the findings will be presented for each system individually.

The Pavegen® system is installed on the ground floor of Leighton Buzzard train station. It transfers the kinetic energy of pedestrians into electrical energy. However, Pavegen® didn't provide the data of number of footsteps, and the generation data couldn't be assessed due to the changes of structure and licencing of the Siemens platform that Pavegen® has been using. Cranfield University (CU) has only received the initial generation data from 1/June/2022 to 31/July/2022 to carry out the analysis. Therefore, the analysis for efficiency, real-time performance, performance deterioration over time, and any potential changes in performance characteristics due to seasonal usage patterns couldn't be implemented due to lack of data. The provided data enabled the analysis of energy quantity assessment in day/night, weekdays/weekends, and the evaluation of environmental and economic impacts. Yet, it could be argued that technologies like Pavegen® may generate further social benefits in terms of public awareness to energy technologies and the need for alternative forms of energy generation to support transition to net-zero. In this project, these types of values are not investigated due to resource constraints.

The WattWay® system is a trafficable photovoltaic (PV) surfacing which is designed to convert solar energy to electricity to power the equipment (such as the power traffic signs and streetlights) near the roadway. By using generation, solar irradiance, and cell temperature data for 00:00 12/12/2021 to 00:00 28/11/2022, this report evaluates the performance of WattWay® system in terms of derating factor and efficiency, and economic and environmental impacts. It is found that the average efficiency of WattWay® is between 8.2% and 10.2% before the failure of electrical components (which are independent from the WattWay® panels technology, as claimed by the company). This value is lower than the average yield of 18.2% as presented in WattWay® technical datasheet; the efficiency further drops to 3.3% after the failure, and reaches to 5.8% after its fixing.

The Power Road® system stores the heat in summer to the borehole and use heat pumps to support the thermal demand for buildings and de-icing of parking surface. This report analyses the performance of the Power Road® system as well as its economic and environmental impacts. It is found that the performance of Power Road® system is inefficient, the coefficient of performance (COP) of heat pump is approximately 1.65, which is much lower than the Carnot COP value of 7.2 and the rated COP of 4.2 for Kensa heat pump used in Power Road®.

# 2 Pavegen®: Energy Quantity Assessment

## 2.1 Data setup

The generation data from 1/June/2022 to 31/July/2022 is collected from Pavegen® with irregular time series, this is because that the data is only recorded when people step on it. The data is re-arranged to hourly data in this report for the ease of analysis. The generation from Pavegen® over the two months is depicted in Figure 1. The maximum power generation is 0.57 kWh. While post-Covid changes in train travel patterns via reduced human activities would have a direct impact on the amount of energy generated, other factors like train strikes on 21, 23 June and 27 July have resulted in lower generation than the other days.

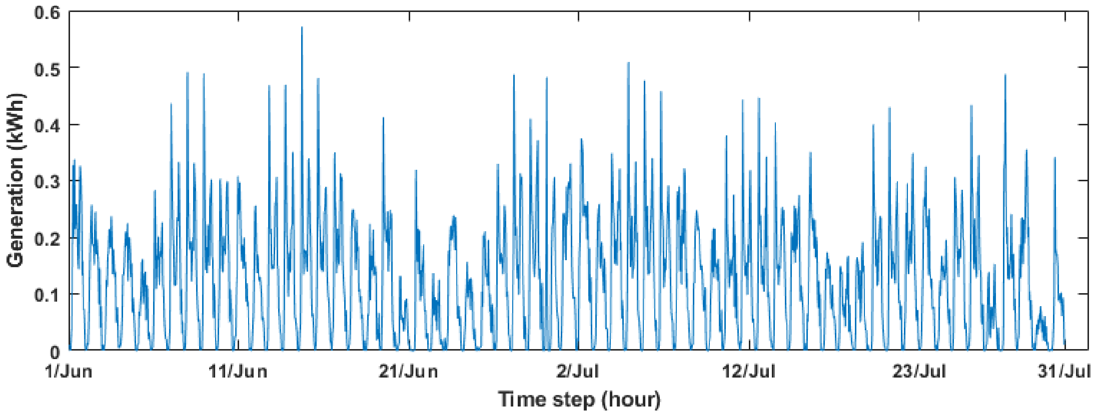

Figure 1 Pavegen® Energy generation from 1/Jun to 31/Jul

## 2.2 Energy generation in day and night

The average hourly energy generation of June and July can be derived as shown in Figure 2. As seen, the generation variations of the two month show similar trends. Taking June as an example, the generation before 4 am is nearly zero due to minimum human activities; then the generation significantly increases from 0.03 kWh at 5am to 0.27 kWh at 7am and 8am because of increased human activities, where people head to work or schools; the generation reduces to 0.17 kWh at 9am then stabilise until 3pm, it then starts increasing and reaching another peak generation of 0.22 kWh at 6pm since people off work and schools; it then gradually decreases to 0.05 kWh at 24:00.

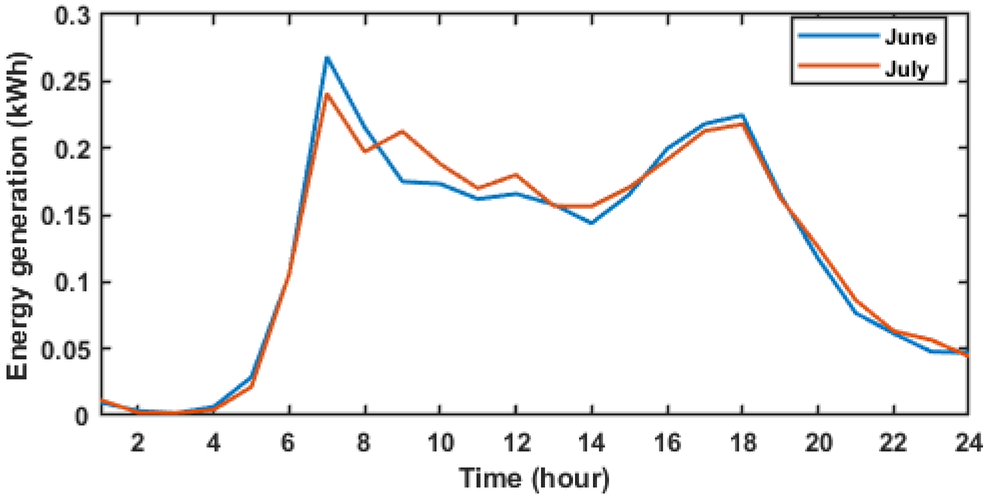

Figure 2 Average hourly generation for June and July 2022

The average hourly generation during daytime (5am to 9pm) and night-time in June are 0.16 kWh and 0.025 kWh respectively.

## 2.3 Energy Generation in Weekday and Weekend

The average hourly generation for weekday and weekend is calculated and shown in Figure 3.

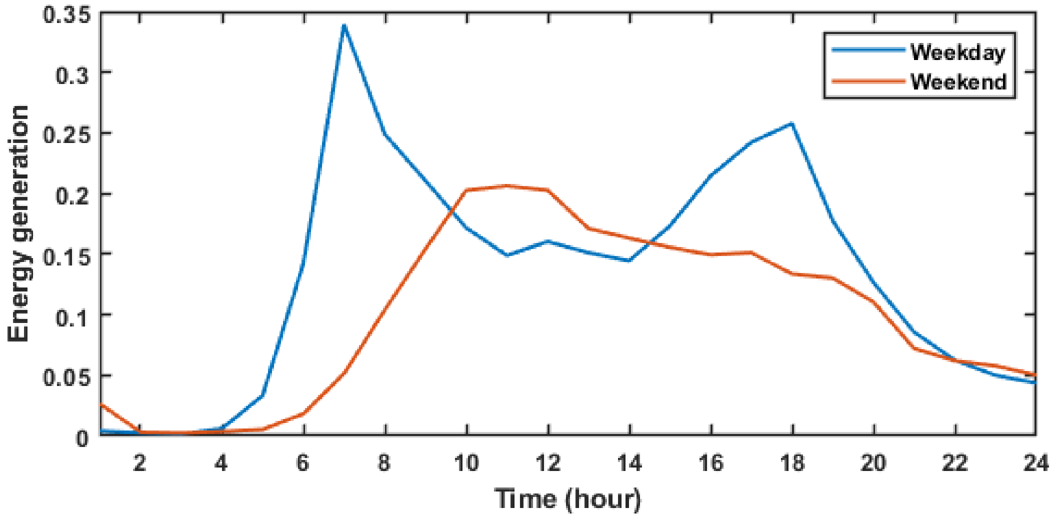

Figure 3 Average hourly generation for weekday and weekend

As seen from Figure 3, the generation in weekdays shows two peaks at 7am with 0.34 kWh and 6 pm with 0.26 kWh, which is due to the increased human activities in walking to work/schools and going back home. At the weekends, the generation reaches a peak of 0.21 kWh between 11am and 12pm, due to higher human activities at midday.

The average daily generation on a weekdays and weekend is 3.20 kWh and 2.39 kWh respectively, indicating higher human activities during the week than at the weekends which is supported by other data[1].

## 2.4 Analysis of Environmental Impact

To evaluate the environmental impact, the carbon intensity (amount of carbon emission per kWh of electricity consumed) data from 00:00 1/6/2022 to 00:00 31/07/2022 in the UK is downloaded from National Grid ESO (https://www.nationalgrideso.com/future-energy/our-progress/carbon-intensity-dashboard) and plotted in Figure 4. The carbon intensity varies between 52 g/kWh and 309.5 g/kWh.

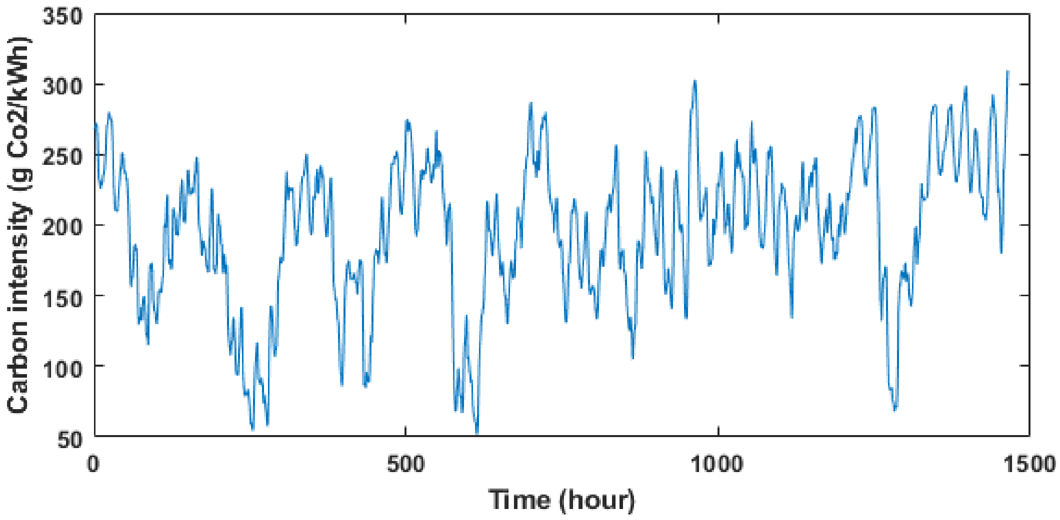

Figure 4 UK Carbon Intensity from 01/Jun/2022 to 31/Jul/2022

The carbon saving because of Pavegen® can be calculated by multiplying the carbon intensity and Pavegen® generation at each hour and adding them together.

It is calculated that in total 34.75 kg of carbon emission was saved from 1/6/2022 to 31/07/2022.

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[1] Rail trips number data from Department for Transport: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/73093/rail-trends-factsheet-2010-11.pdf

## 2.5 Economic Impact

According to Ofgem, the average capped rates of electricity price under energy price guarantee from 1 October 2022 is £0.34/kWh. The economic saving can be calculated by summing the multiplication of Pavegen® generation at each hour and the electricity price.

It is calculated that in total £61.37 of electricity cost was saved from 1/6/2022 to 31/07/2022.

## 2.6 Conclusions

The expected measurement and monitoring data against the plans for the types of analysis that Cranfield University has committed to undertake is summarised in Table 1. As limited data was provided over two months, many of the proposed analysis weren't undertaken.

Table 1. Summary of data provided and analysis performed

| **Expected measurement and monitoring data** | **Assessment** |
|---|---|
| Collect energy generation data from arrays in hourly basis | Partially provided (1 June-31 July 2022) |
| Gather information (e.g. no. of footsteps) from test sites in real time uses of Pavegen® | Not provided |
| Monitor and record faults in arrays or modules on day to day basis | Not provided |
| **Planned analysis** | **Assessment** |
| Analyse energy data and footsteps to inform efficiency of arrays in practice | Completed for the available data |
| Evaluate and contrast real time performance against the specified values provided by the manufacturer | Not completed due to lack of data |
| Calculate and measure performance deterioration of Pavegen® arrays over periods of time (monthly and yearly) | Not completed due to lack of data |
| Compare operation performance to inform its variation in day vs night, week vs weekend and seasonal or festive seasons | Completed for the available data |

This report assesses the energy quantity of Pavegen® in day/night, weekdays/weekends, and evaluates the environmental and economic impacts. The key findings are:

- The Pavegen® generation is highly relevant with human activities, it generates more power in daytime compared with night-time, and the weekday generation is higher than generation in weekends.
- The Pavegen® system saves 34.75 kg of carbon emission and £61.37 of electricity cost from 1/6/2022 to 31/07/2022.

Additionally, some insights are presented as follows:

- Covid lockdown and resulting changes in travel patterns may have impacted the Pavegen® system power generation due to less human activities. While it is difficult to assess how much power would have been generated if there was no lockdown, equally it's difficult to assess how generation may change in the future as there are no robust datasets yet on changing travel patterns.
- Technologies like these could generate further social benefits in terms of public awareness and understanding of energy technologies and the opportunities for alternative forms of energy generation. While it's hard to quantify these social values, they would definitely impact cost-effectiveness of this technology which wasn't investigated in this project.
- The payback period of Pavegen® can be estimated if the cost of installation and maintenance (physical i.e. annual jet wash and IT related) is provided, and if more generation/footstep count data can be provided to simulate the system performance.
- The project team has reported the following lessons learnt in the installation phase: 1) the required depth of drainage system can be reduced such that it outfalls into the road channel, reducing the installation costs; 2) the installation location and its ownership need to be taken into account as in this case the land was owned by Network Rail, and is managed by WMTrains on behalf of Network rail. The team needed to enter into a license agreement with both Network Rail and WMtrains before installation. The installation needed to follow the Network rail construction guidelines and standards for installation. The proposed installation with drawings and method statements, specifications are needed to be sent to WMtrains and Network Rail as part of the license agreement. The works could only start once the team had the license and agreement signed by all parties. Any future installation needs to take into account the ownership of land and any 3rd party requirements.

# 3 Performance Evaluation of WattWay® System

This section firstly illustrates the indicator for evaluating the PV performance – the PV derating factor, and then presents the WattWay® system performance from 00:00 12/12/2021 to 00:00 28/11/2022, where the system inefficiency and reasons are also discussed.

## 3.1 Background: Solar PV Derating factor

The derating factor is applied in this report to evaluate the performance of solar PV. It describes the reduction of solar PV output deviated from the expected output under ideal condition (when the PV panel was rated) due to the factors such as the temperature variations, wiring losses, shading, dust on the panel surface, etc [1]. The derating factor has been widely applied in many simulation software to calculate solar PV output, such as Homer PRO. A derating factor of 1 means that the PV panels are installed and operated in an ideal condition. The PV derating factor $f_{PV}$ can be expressed by:

$$f_{PV} = \frac{P_{PV}}{P_{PV,STC}\left(\frac{I_T}{I_{T,STC}}\right)[1+\alpha_P(T_c-T_{c,STC})]} \tag{1}$$

Where $P_{PV}$ represents the PV power output in kW, $P_{PV,STC}$ is the rated capacity of the PV under standard test conditions, in this case 27 kW; $I_{T,STC}$ is the solar irradiation at standard test conditions (1 kW/m$^2$), $I_T$ is the solar radiation incident on the PV array in kW/m$^2$, $T_{c,STC}$ is the PV cell temperature at standard test conditions (25 ˚C), $T_c$ is the PV cell temperature during operation. $\alpha_P$ is the power temperature coefficient (%/˚C), which indicates the impact of solar cell temperature to solar PV output; the value is normally between -0.5 %/˚C and -0.3 %/˚C.

## 3.2 Overview of WattWay® Power Output

Hourly data including PV generation, solar irradiance, and cell temperature from 00:00 12/12/2021 to 00:00 28/11/2022 has been provided by WattWay®; there are missing data points for solar PV output and irradiance, such as at 12:00 on 4th September 2022, those missing points are removed to ensure the consistency and accuracy of analysis. In total 8424 number of derating factors are calculated based on the provided data. However, 8 of them are over one, which represents possible measurement errors for these datapoints. For the purpose of data analysis, the abnormal derating factors are replaced by the mean value of derating factors across the time window.

The monthly cumulative energy generation from WattWay® and cumulative solar irradiance are plotted in Figure 5.

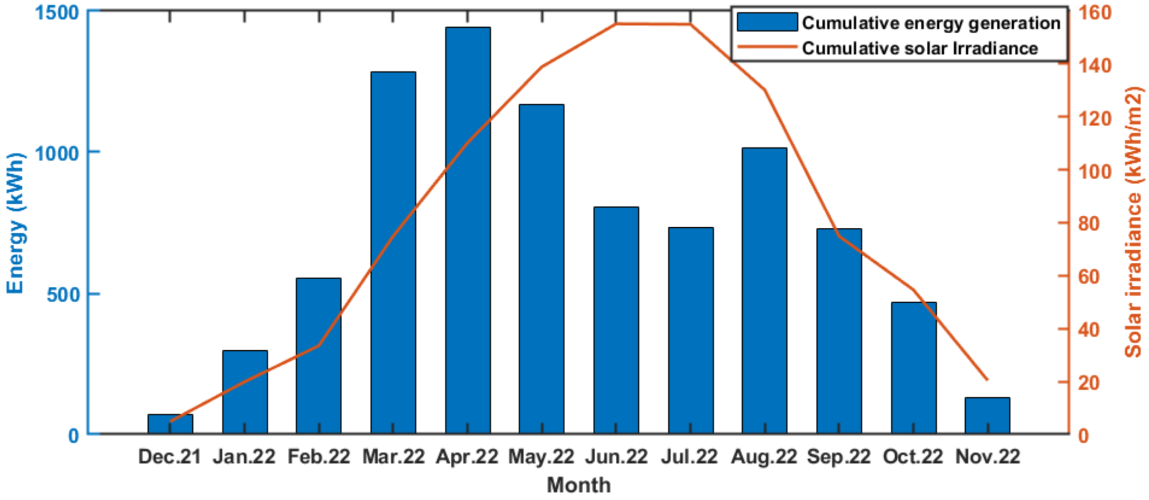


Figure 5. **Monthly cumulative energy generation from WattWay® and monthly cumulative solar irradiance from December 2021 to November 2022**

As seen in the orange line of Figure 5, the monthly solar irradiance increases from 4.91 kWh/m$^2$ in December 2021 to 155.14 kWh/m$^2$ in June 2022, and then gradually decreases to 20.40 kWh/m$^2$ in November 2022. The solar irradiance of summer is higher than in the winter due to longer daytime and sunnier weathers. It should be noted that the cumulative power generation observed in December 2021 is much lower than other months because only 20 days of data was recorded and used for deriving the figure.

The blue bars in Figure 5 show the monthly power generation from the WattWay® system, the generation increases from 71.64 kWh in December 2021 to 1441.61 kWh in April 2022, then decreases to 734.53 kWh in July 2022; the output of generation in August 2022 is 1014.94 kWh, which is higher than in July, but the output then keeps reducing to 130.97 kWh in November 2022.

The power generation keeps reducing from April to July despite the increase of solar irradiance in these months. The installation company informed us that this is because the electrical components (independent from the WattWay® panels technology) experienced a few failures including one power conditioner and several DC-to-DC converters in summer, affecting the power generation. The manufacturer later replaced some pieces of equipment, and hence the power output restored to 1015 kWh generation in August 2022 according to Figure 5. The power generation reduces from August 2022 to November 2022 due to the decrease of solar irradiance.

## 3.3 Derating factor

To assess the performance of WattWay®, the hourly derating factor of WattWay® system is calculated by equation (1) based on the data collected from the site. The hourly derating factor is shown in Figure 6.

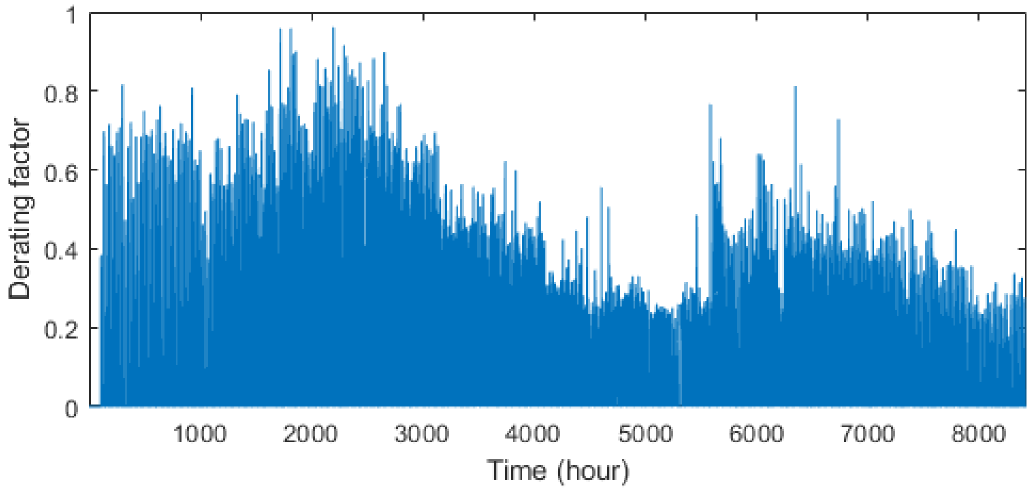


Figure 6 Hourly derating factor of WattWay® system

The highest derating factor, as displayed in Figure 6, is 0.96, which indicates a near-ideal operating condition. Overall, the derating factor maintains at a relatively high level in winter, but starts to drop during summertime, which may be due to the failure of electrical components noted above. To better observe the variation of derating factor, the average and maximum derating factors of each month are calculated and shown in Figure 7.

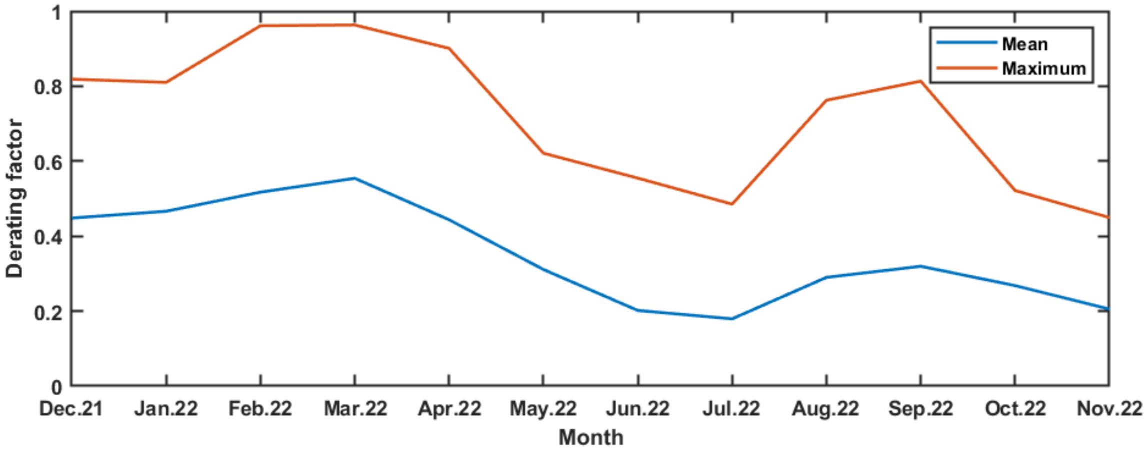


Figure 7 Average and Maximum derating factors of each month

As seen from Figure 7, the mean and maximum derating factors of each month show similar varying trends. The mean derating factor gradually increases from 0.45 in December 2021 to 0.55 in March 2022, then decreases to 0.18 in July 2022, it reaches to 0.32 in September 2022 then reduces to 0.21 in November 2022. The figure indicates that the derating factor is likely to increase with the increase of solar irradiance until March, however, the derating factor and performance of WattWay® system drops from April to July 2022 due to the electrical components failure; it restores to a relatively higher level in August and September 2022 after the replacement of fault components, but the derating factor in these months is still lower than the pre-fault period between December 2021 and March 2022. This means that the performance of the trial site didn’t recover to pre-fault level after fixing the faults.

## 3.4 Efficiency

The efficiency of WattWay® can be calculated by

$$\eta = \frac{P_{PV}}{A_{PV} \cdot I_T} \tag{2}$$

Where $P_{PV}$ is the power output from PV in kW, $I_T$ is the solar radiation incident on the PV array in kW/m$^2$, $A_{PV}$ is the area of solar PV in m$^2$. There are 216 solar modules being installed in the trial site, and the area of each module is 0.69 m$^2$ according to WattWay® technical datasheet, hence the area of solar PV is calculated as 216*0.69=149.04 m$^2$. By using (2), the average efficiency of WattWay® of each month can be calculated and shown in Figure 8. It should be noted that the efficiency was re-calculated and updated based on the correct dataset provided by WattWay®.

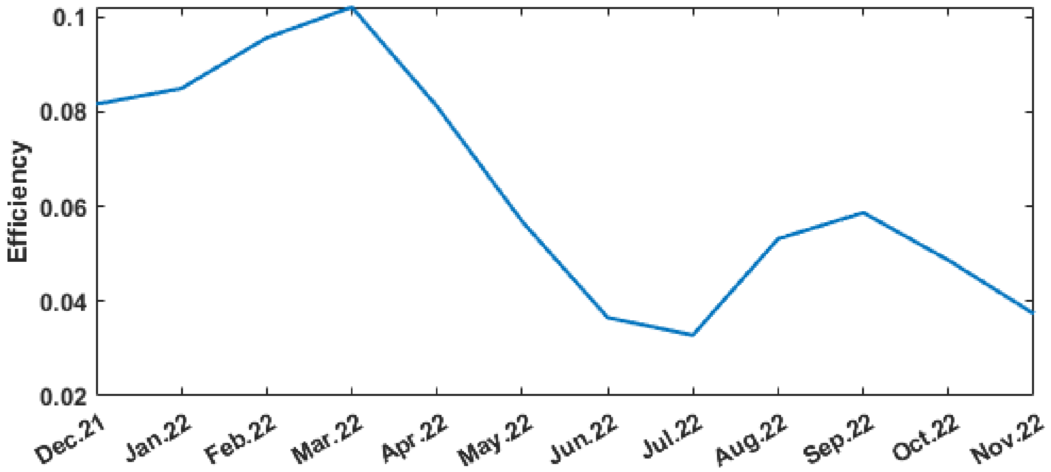


Figure 8 Mean efficiency of each month

As seen from Figure 8, the mean efficiency is between 8.2% to 10.2% before the failure of electrical components noted above, however, it is lower than the average yield of 18.2% in WattWay® technical datasheet. The efficiency drops to 3.3% in July 2022, then increases to 5.8% in September, this also indicates that it did not recover to pre-fault level.

## 3.5 Energy Quantity Assessment

The average of hourly generation over 24 hours from WattWay® is depicted in Figure 9 for each month. The horizontal axes represent the time in hour, and the vertical axes represent the energy generation in kWh. As observed, the power output follows the variation of solar irradiance, it starts to generate power in the morning from 5am or 9 am depending on the season, reaches to maximum power output at around noon, and decreases to 0 at a time period between 4pm and 9pm depending on the season.

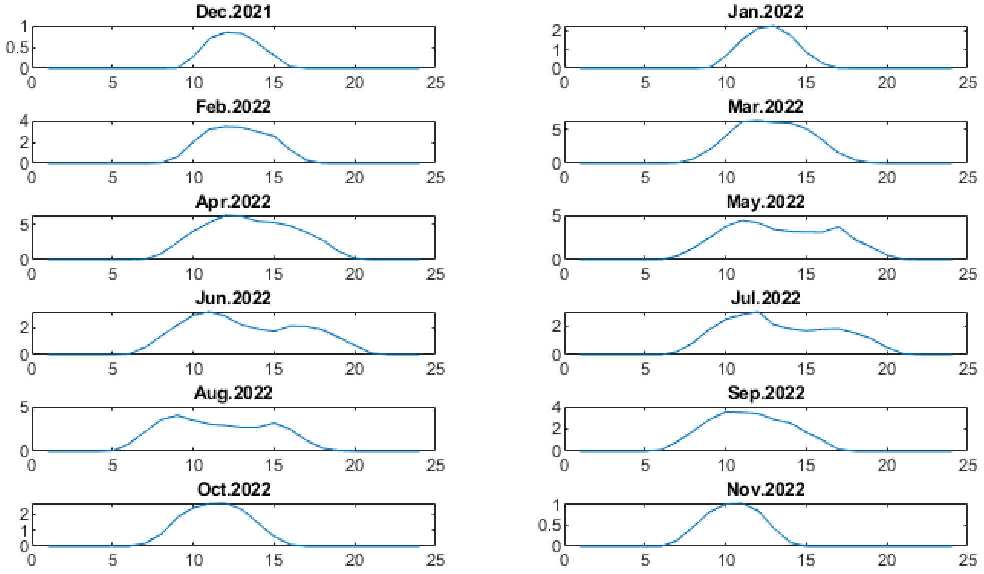


Figure 9 Average hourly generation of each month

The average of daily total power generation of each month is depicted in Figure 10. As seen, the daily total power generation increases from 3.58 kWh in December 2021 to 48.05 kWh in April 2022, it then reduces to 23.70 kWh in July 2022 due to the failure of electrical components, it increases to 32.74 kWh in August, and further reduces to 4.85 kWh in November 2022.

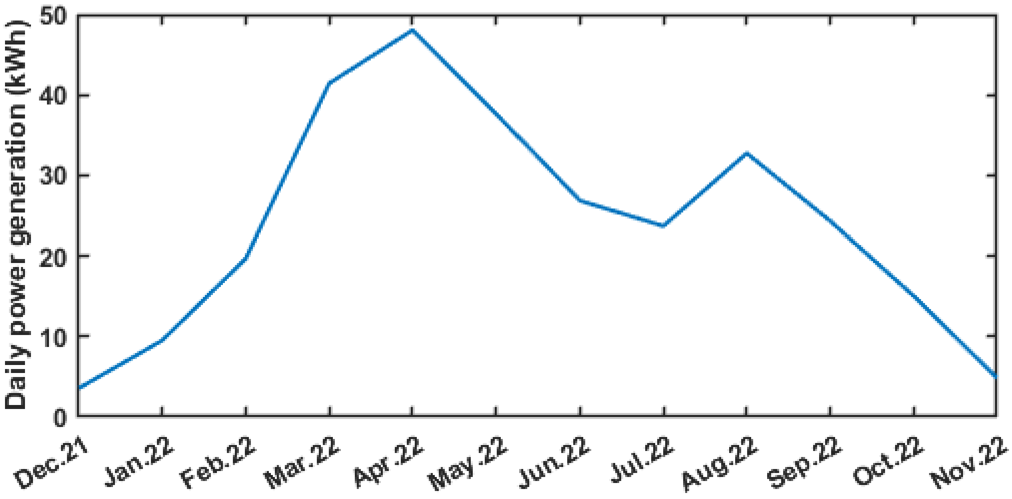


Figure 10 Average of daily total power generation of each month

## 3.6 Assessment of Possible Applications of WattWay®

### 3.6.1 Streetlights

According to [2], the power of streetlight is normally between 25 W and 250 W, its power rating is relatively high when it's placed alongside the road, and it's low when installed in parks and pedestrian areas. The rated power of streetlight analysed in this report is assumed to be 100 W.

The daily electricity demand of one streetlight in each month is calculated by its power (100W) multiplied by the lighting hours, where the lighting hours are derived based on the duration of night-time in each month (according to https://www.worlddata.info/europe/united-kingdom/sunset.php), the electricity demand of one streetlight is shown in the orange line in Figure 11. As seen, the demand is higher in winter due to longer night-time, and lower in summer due to much shorter night-time.

The number of streetlights that WattWay® can power for each month is calculated by using the daily generation from WattWay® as in Figure 10 divided by the daily demand of one streetlight; it is plotted as in the blue bars in Figure 11. It can only power 2 to 3 streetlights in winter due to higher electricity demand and lower energy generation, but it's capable of powering more streetlights in the range between 30 and 50 in summer because of lower electricity demand and higher energy generation.

However, it should be noted that, power is only generated from WattWay® during daytime, hence it cannot be directly used to power the streetlight since the demand is at night. Other devices such as batteries should be used to store the WattWay® generation during daytime, and discharge at night to power the streetlights.

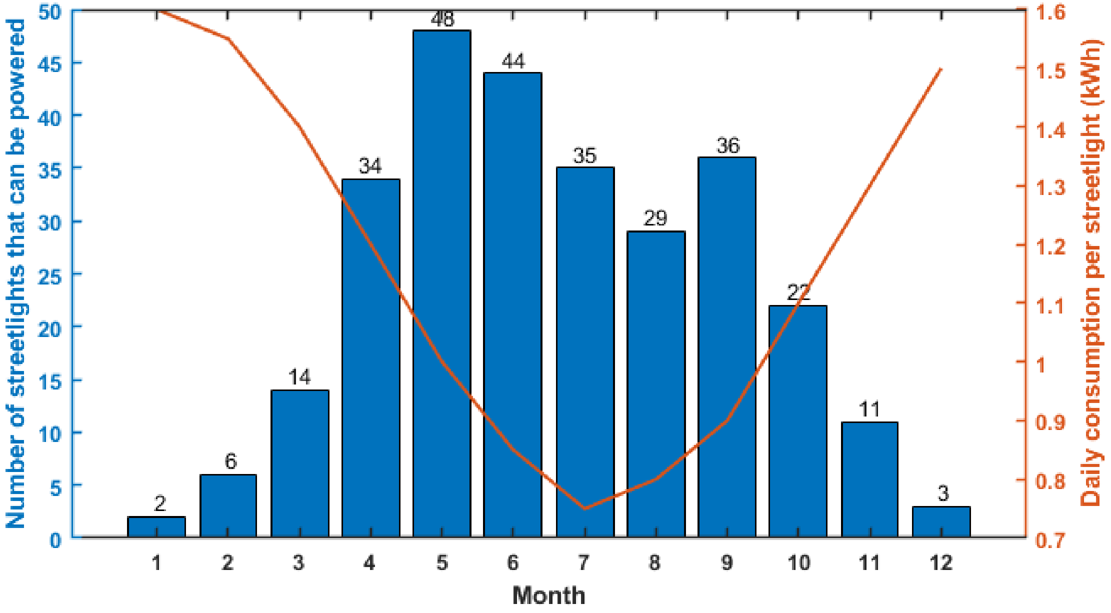


Figure 11 Number of streetlights that WattWay® can power for each month (blue bars) and daily total electricity demand per streetlight (orange line)

### 3.6.2 Other applications

In addition to streetlights which requires electricity outside the generation hours of WattWay®, other applications could be explored. For example, electricity demand in adjacent buildings, such as for lighting, during daytime can be powered by WattWay®. Alternatively, electric vehicle or e-bike charging stations can use the electricity generated from WattWay® to charge electric vehicles/e-bikes. Other applications could include powering CCTV cameras, bike and traffic counters. All these applications would reduce the cost of purchasing electricity from the grid.

## 3.7 Environmental Impact

To evaluate the environmental impact, the carbon intensity (amount of carbon emission per kWh of electricity consumed) data from 00:00 12/12/2021 to 00:00 28/11/2022 in the UK is downloaded from National Grid ESO (https://www.nationalgrideso.com/future-energy/our-progress/carbon-intensity-dashboard) and plotted in Figure 12. The carbon intensity varies between 39.5 g/kWh and 322 g/kWh.

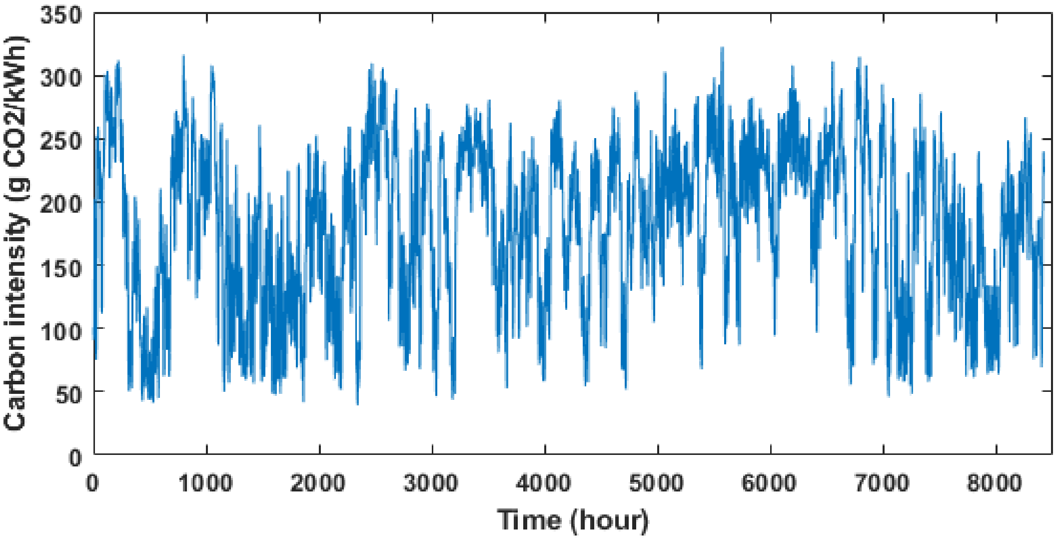


**Figure 12 UK Carbon Intensity from 12/12/2021 to 28/11/2022**

The carbon saving because of WattWay® can be calculated by multiplying the carbon intensity and WattWay® generation at each hour and adding them together.

It is calculated that 1.52 ton of carbon emission was saved from 12/12/2021 to 28/11/2022.

## 3.8 Economic Impact

According to Ofgem, the average capped rates of electricity price under energy price guarantee from 1 October 2022 is £0.34/kWh. The economic saving can be calculated by multiplying WattWay® generation at each hour and the electricity price. It is calculated that £2,956.2 was saved from 12/12/2021 to 28/11/2022.

## 3.9 Installation cost

Colas reported that the installation cost of WattWay® system was over €200k while they couldn't provide further details. The company claims that the installation costs could be reduced up to 30% due to cost trajectories for PV and the fact that the CBC installation was the first installation in the UK. This wasn't evaluated in the report.

## 3.10 Conclusions

The expected measurement and monitoring data against the plans for the types of analysis that Cranfield University has committed to undertake is summarised in Table 2. As limited data was provided over two months, many of the proposed analysis weren't undertaken.

**Table 2. Summary of data provided and analysis performed**

| **Expected measurement and monitoring data** | **Assessment** |
|---|---|
| Collect energy generation data from WattWay® trial sites in hourly basis | 00:00 12/12/2021 to 00:00 28/11/2022 |
| Gather solar intensity, temperature and atmospheric condition data from WattWay® automatic management system; angle of irradiance information for test sites | 00:00 12/12/2021 to 00:00 28/11/2022 |
| Record faults in solar PV arrays | Not provided |
| Measure maintenance time requirement | Not provided |
| **Planned analysis** | **Assessment** |
| Compare real time energy generation data from the test sites with manufacturer data | Partially complete as manufacturer data wasn't available |
| Investigate and conclude any inefficiency and reasons for it | Not completed due to lack of data |
| Assess energy quantity and possible allocations to roadside lights, signals, adjacent developments and, if possible, to the grid | Completed for the available data |
| Develop performance mapping of WattWay® under different solar irradiances measured in the test sites (seasonal variations). | Completed for the available data |
| Assess environmental impacts from the implementation of WattWay® | Completed for the available data |
| Evaluate cost savings from WattWay® | Completed for the available data |

Overall, we analysed the performance of the WattWay® system based on the near-one-year data collected from the trial site. We assessed possible allocation of WattWay® power to potential adjacent uses, and calculated environmental and economic impacts. Our key findings are as follows:

- Electrical equipment failure (independent from the WattWay® panels as claimed by the WattWay® operator, Colas) happened during summer, which has significantly affected the WattWay® output.
- The average derating factor is around 0.5 before the failure of electrical components, it drops to 0.2 when the faults happen. The derating factor was around 0.3 and didn't reach the pre-fault level when WattWay® operator (ie Colas) fixed the faults.
- The average efficiency before the failure of electrical components is between 8.2% and 10.2%, which is lower than average yield of 18.2% as presented in WattWay® technical datasheet.
- The WattWay® system can support 2-3 streetlights in winter, and up to 50 streetlights in summer. However, battery storage has to be applied to store WattWay® generation in daytime, and discharge to support the streetlights at night.
- The WattWay® system saves 1.52 ton of carbon and £2956.2 of electricity costs from 12/12/2021 to 28/11/2022.

Additionally, some insights are:

- The project team at Central Bedfordshire Council (CBC) noted the difficulties for maintenance when this technology is installed on public highway network. They noted that the WattWay® system could be better managed when installed in a depot.
- The CBC team also noted contractual issues emerging from the project. They clarified that there wasn't a maintenance contract for this experimental site. When certain electrical components failed, they didn't receive any warnings. The monitoring system allows CBC to track power generation and any functioning defects, but because these defects didn't create any warnings to the team, and CBC were not looking at the system regularly, they weren't acted upon immediately, causing delays in their maintenance.

# 4 Power Road®

Broadly, Power Road® system has 3 different layers (Figure 13), including the *utility, heat pump and heat source (borehole).* Furthermore, there are two main operation modes in the system, namely *summer and winter modes*.

In summer-mode operation, heat absorbed from the ground surface of the park road is transmitted to the borehole via the distribution loop.

In winter-mode operation, heat pumps are used to retrieve heat from the borehole and transferred to the utility, which will be used to support the *heating demand for buildings* and *parking surface de-icing (Power Road®).*

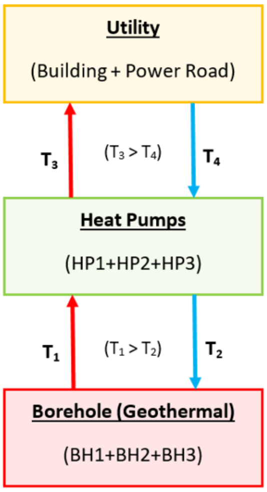


Figure 13. Power Road® System main components

A more detailed diagram of the system is presented in Figure 14.

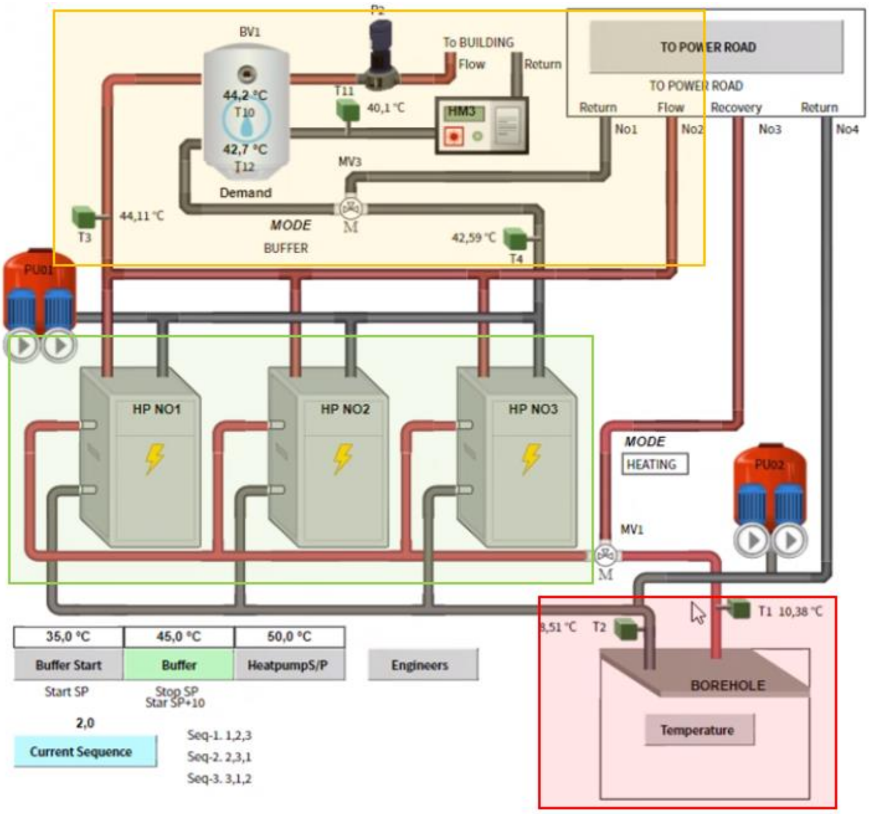


Figure 14. Schematic of Power Road® System

## 4.1 Performance Evaluation

This section firstly presents the operating mechanism of the Power Road® system and explains the measured data; it then evaluates its performance. The performance analysis has three components: i) the performance of heat pumps; ii) assessment of their Coefficient of Performance (COP) based on the measured temperatures; iii) economic and environmental impacts of applying the system against using natural gas and salt for heating and de-icing.

## 4.2 Distribution of Heat to Road and Adjacent Building Based on the Available Heat Stored in Underground

As shown in Figure 15, inlet and outlet temperature of the hot water to adjacent building is measured through T10 (in) and T11 (return), and amount of heating energy is measured via heat meter-3 (HM3). The inlet and outlet temperature of the hot water for de-icing line is measured through T7 (in) and T8 (return). Amount of heating energy is measured via heat meter-1 (HM1).

According to the schematic provided by the company, the heating load of the adjacent building and Power Road® are 5 kW and 41 kW, respectively. These values are circled in Figure 15.

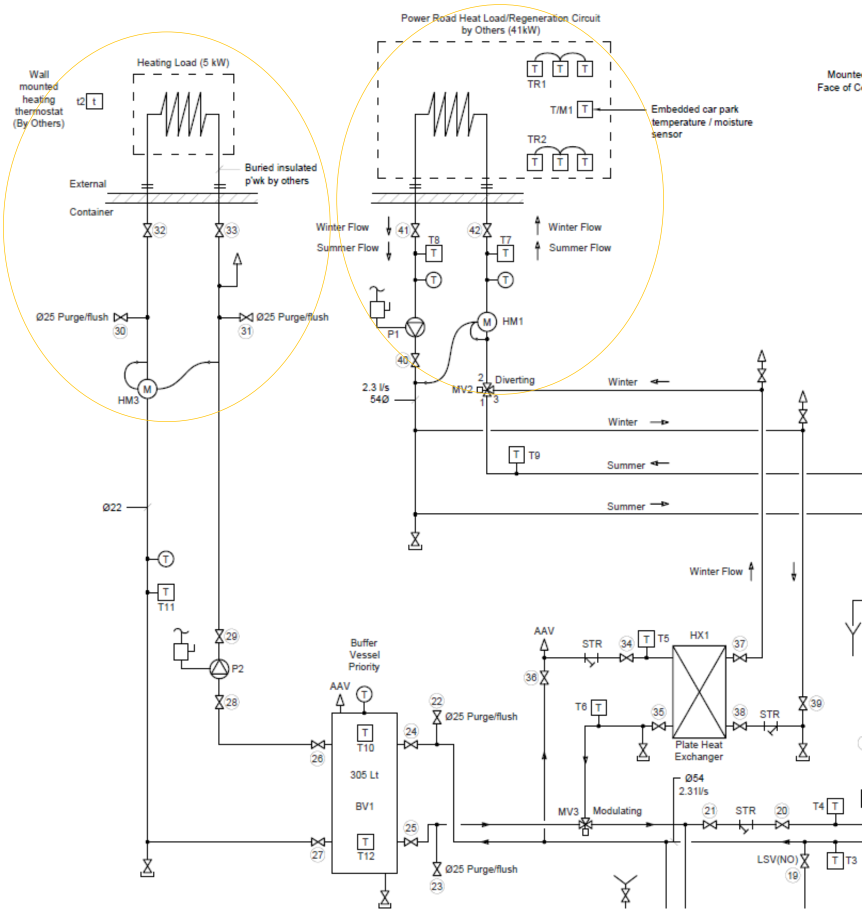


Figure 15. Schematic presentation of resource flows

From May 2021 to Nov 2022, the temperature changes of distribution lines to the building (T10 and T11) are presented in Figure 16 and Figure 17, respectively.

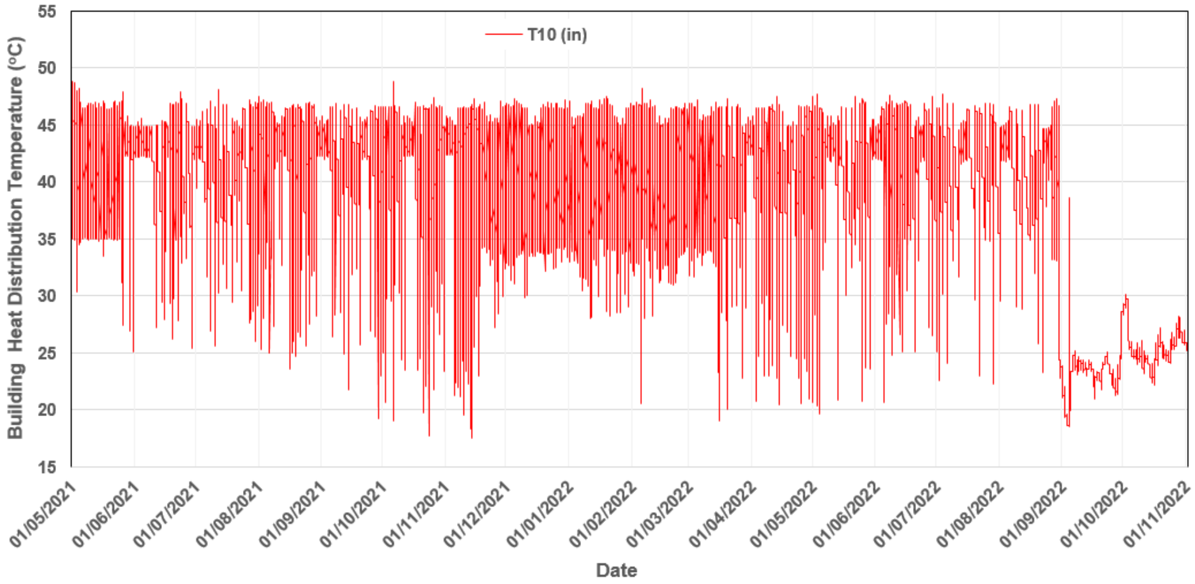


Figure 16. Building heat distribution line inlet temperature

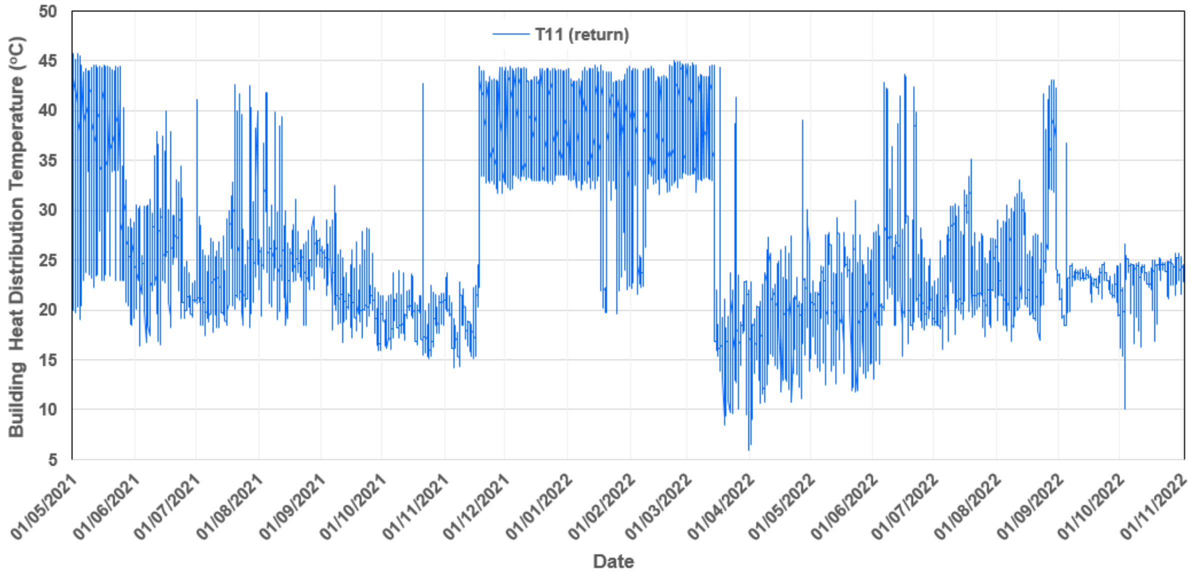


Figure 17. Building heat distribution line return temperature

The heating demand of the adjacent building is either for space heating (in winter) or supporting domestic hot water (winter and summer). The temperatures of the building distribution line (i.e. the line from heat pumps to the building) as presented in Figure 16 and Figure 17 vary across the seasons. The temperatures are high in summer because of the hot water demand.

Through the year, the temperatures changes of the heat distribution line for de-icing (T7 and T8) are presented in Figure 18 and Figure 19, respectively.

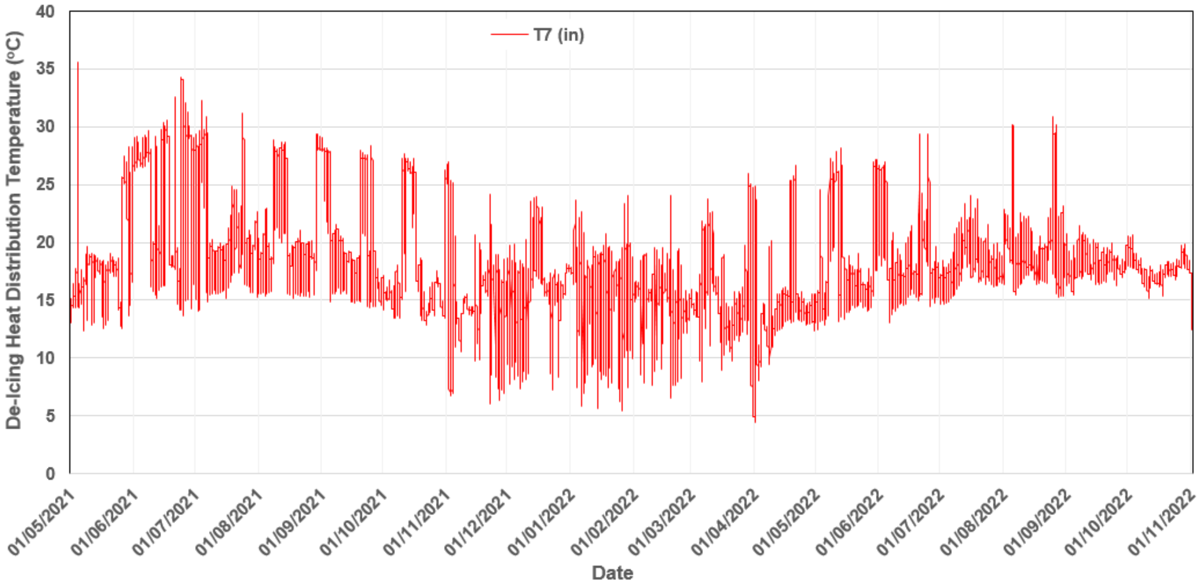


Figure 18. De-icing heat distribution line inlet temperature

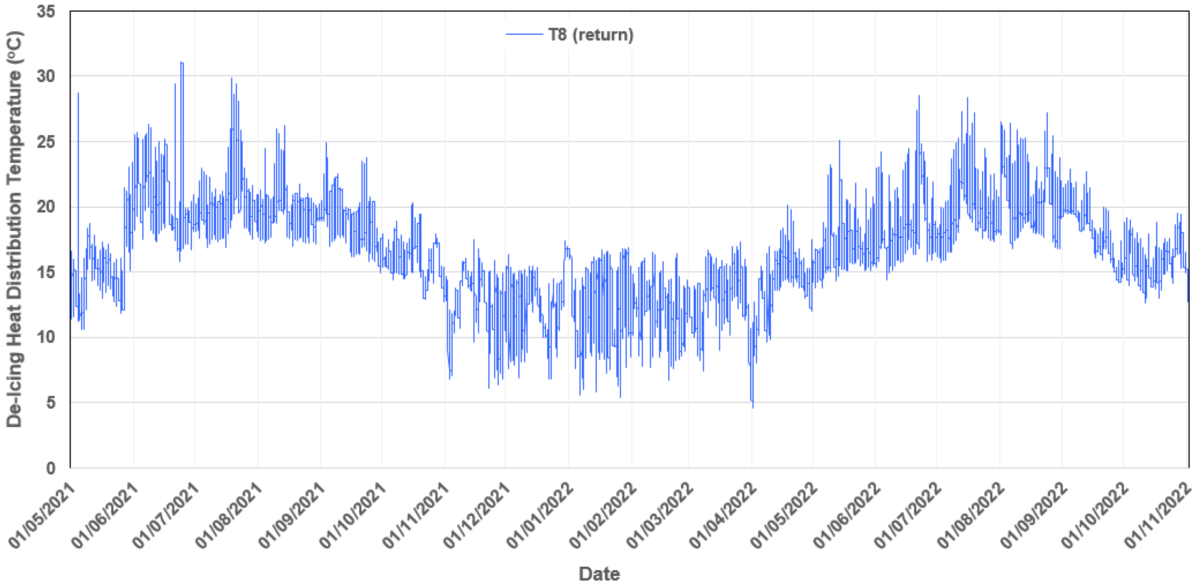


Figure 19. De-icing heat distribution line return temperature

In summer, harvested thermal energy from the road surface because of solar irradiation is transferred to the borehole. Therefore, there is a temperature difference between T7 and T8 during summer. The average temperature of the road, which is measured 10 cm beneath the surface, is presented in Figure 20. Since the measurement is taken at 10 cm of depth, the surface temperature of the road could be lower than the measured value. As seen from the Figure 20, after November the road temperature falls below 10 $^{o}$C. The exact number of icy days is crucial to calculate required salt and gas usage for de-icing.

The heat pumps provide heat flow for the de-icing distribution line when the temperature is lower than 10ºC. As seen from Figure 18, the inlet temperature (T7) of the de-icing line is around 15ºC.

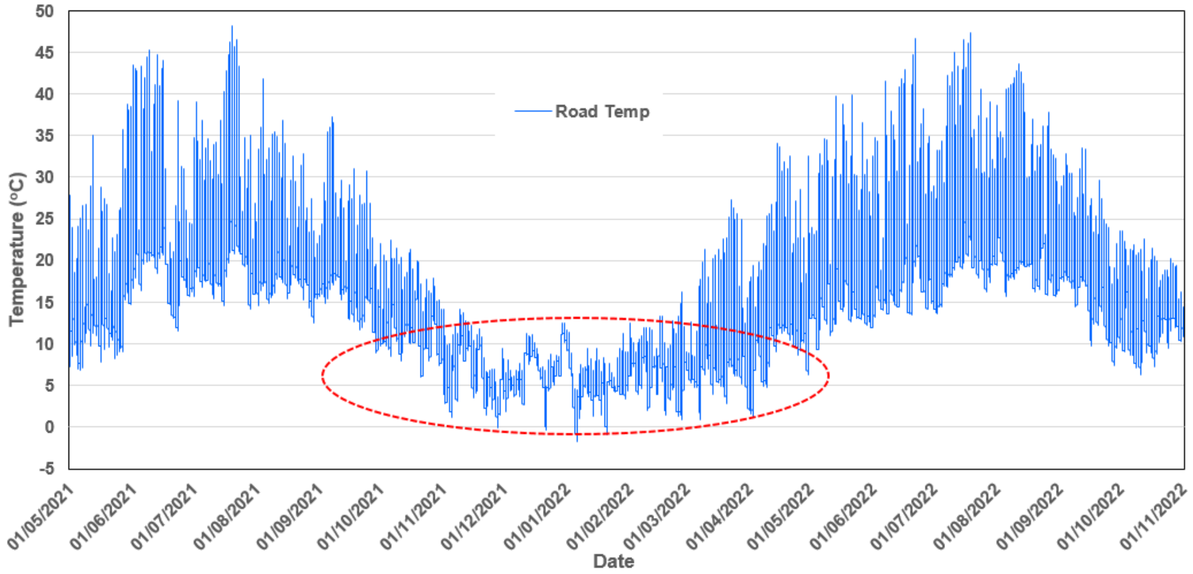


Figure 20. Power Road® temperature

Figure 8. Power Road® temperature

The borehole temperature (TB1 to TB5) and heating energy measuring (HM2) points are presented in Figure 21.

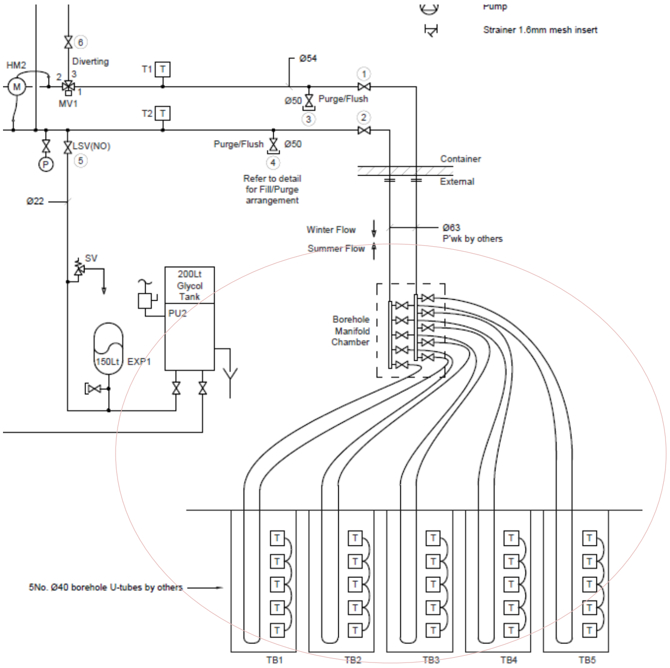


Figure 21. Schematic of boreholes distribution lines

The temperatures of the heat distribution lines (T1 and T2) and boreholes are given in Figure 22, Figure 23 and Figure 24, respectively.
Extracted heat from the geothermal source to the heat pumps is estimated to be at least ~35-40 kW (if all heat pumps are in operation). The temperature changes of heat distribution line (T1 and T2) from May 2021 to Nov 2022 are given below.

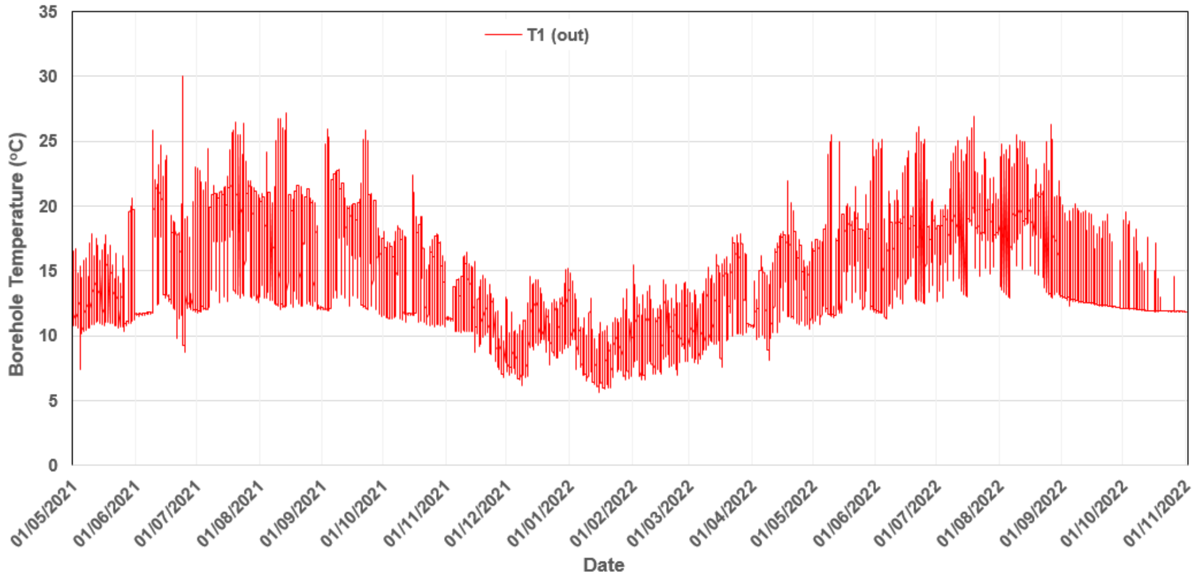


Figure 22. Borehole heat distribution line outlet temperature

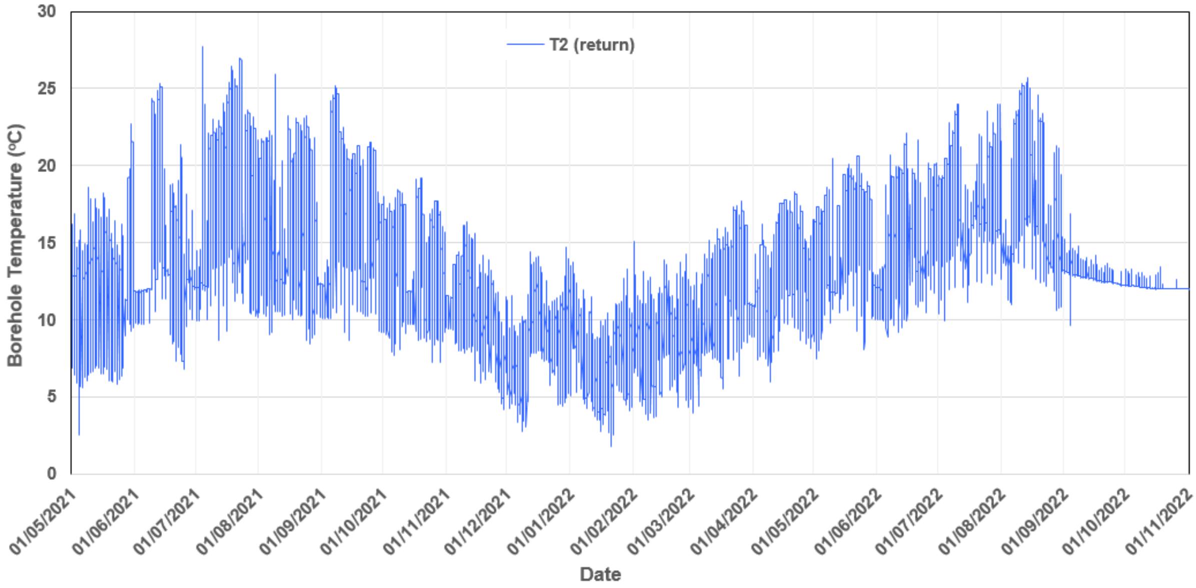


Figure 23. Borehole heat distribution line return temperature

The borehole system can be used for storing heat in summer, where the heat energy due to solar irradiation is harvested from the park road surface and transferred to the boreholes, leading to a high borehole temperature in summer.

The average temperature of the boreholes (S3_5) is presented in Figure 24, which is ~13°C on average through the year. During the winter season, 12 °C is a very good temperature level for efficient operation of heat pumps [3,4].

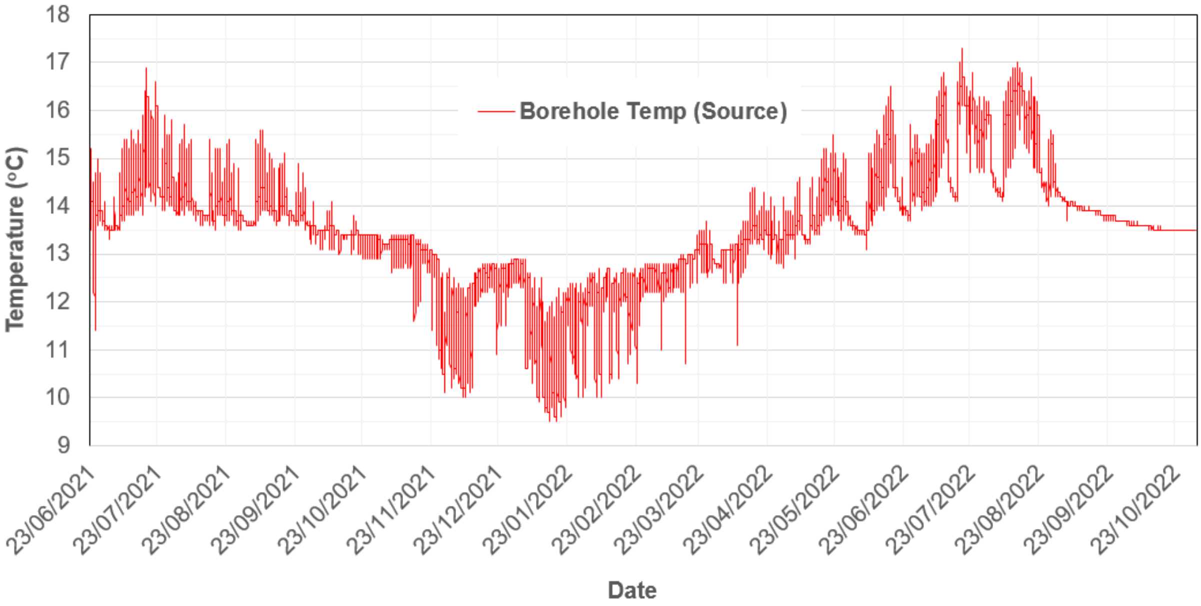


Figure 24. Average temperature of the boreholes (S3_5)

## 4.3 Heat Quantity and Efficiency Evaluation of Transferred Heat for De-Icing and Heating Adjacent Buildings

The amount of heating energy to the utility line is presented in Figure 25. The amount of heating energy delivered to the adjacent building is closed to the designed load (5 kW). On the other hand, the heat delivered to the de-icing line is very limited with 0.074 kW (the orange line) and much lower than the expected load of 41 kW.

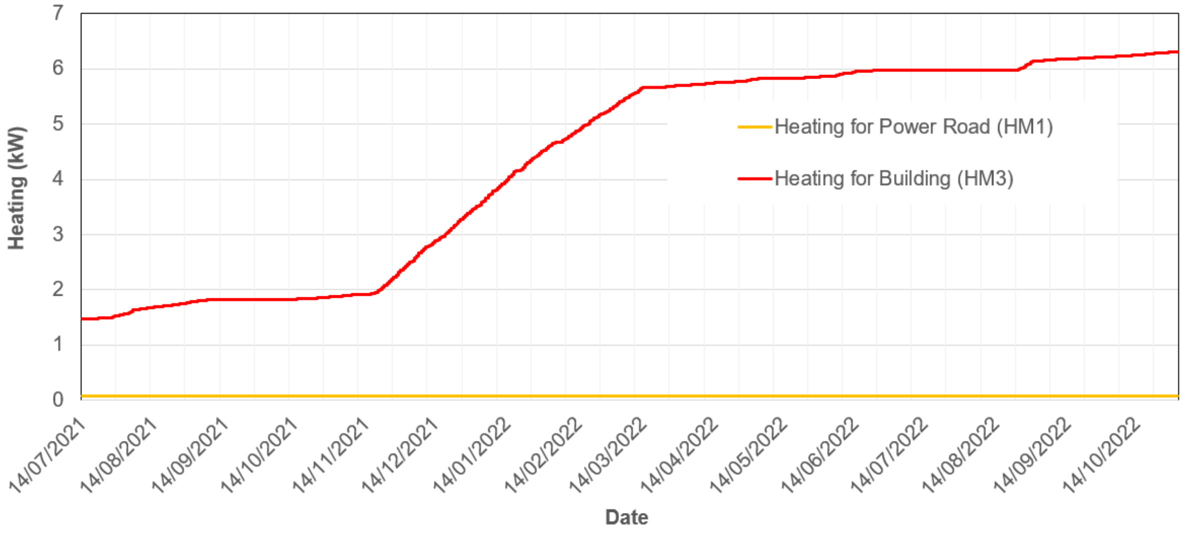


Figure 25. Amount of heat distributed to utilities

The heat retrieved from the boreholes is presented in Figure 26 which seems to increase gradually from July 2021 to over 10kW by February 2022. Any robust inferences would require access to further detailed datasets for longer periods.

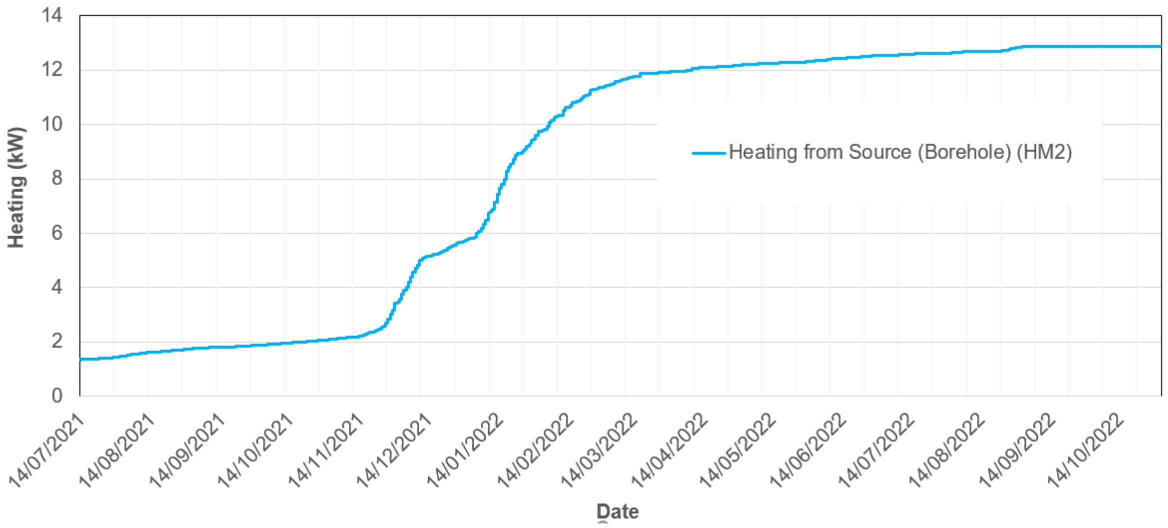


Figure 26. Amount of heat extracted from utilities

## 4.4 Evaluation of Coefficient of Performance (COP) of Heat Pumps

The schematic of the heat pumps and distribution lines are presented in Figure 27. There are 3 heat pumps, each with 15 kW of capacity.

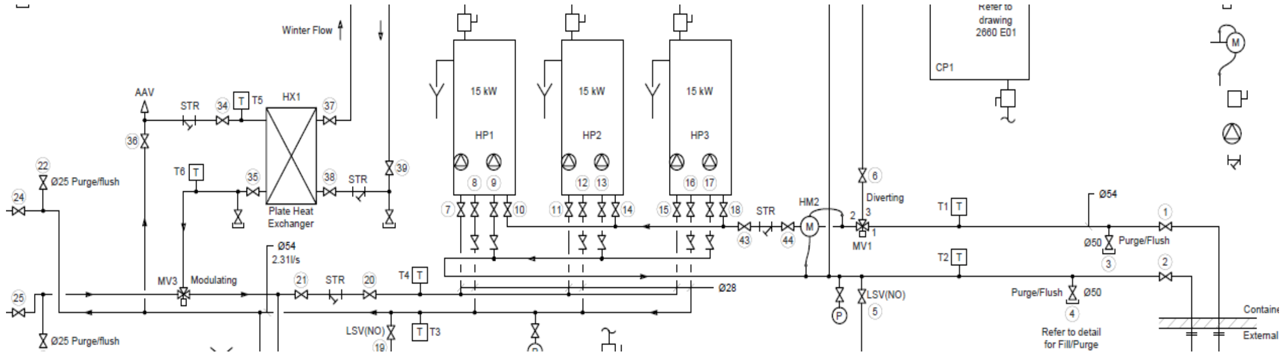


Figure 27. Heat pumps and distribution lines

These heat pumps extract heat from the borehole and deliver it to the utility side (Figure 28).

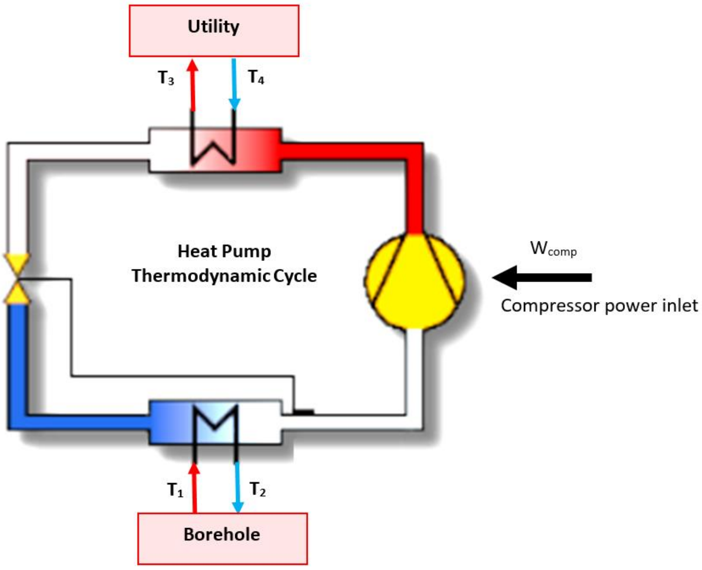


Figure 28. Heat pump cycle between the source and utility

Based on the readings from borehole and hot water side temperatures, it is reasonable to assume that, thermodynamically, the evaporator and condenser of heat pumps operate between the temperature levels of ~5 and 50 $^{o}$C. For the given temperature levels, Carnot Coefficient of Performance ($COP_{Carnot}$), namely the maximum theoretical COP, from these temperature levels is calculated as ~7.2. However, the average COP of heat pumps in the Power Road® system during heating seasons is calculated as 1.65 based on the measurements. Furthermore, based on the measured values, the Second Law efficiency of heat pumps is calculated as ~21%. The COP variations for the duration of analysis is presented in Figure 29.

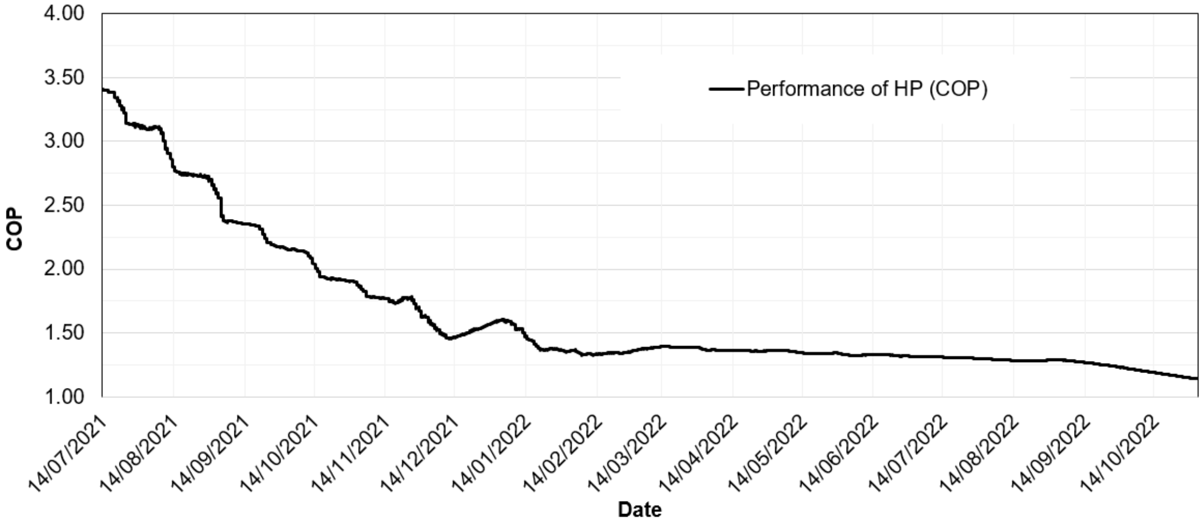


Figure 29. The COP change of the heat pumps

The outlet and return temperatures (T3 and T4) of heat pump's heating energy distribution line are presented in Figure 30 and Figure 31, respectively.

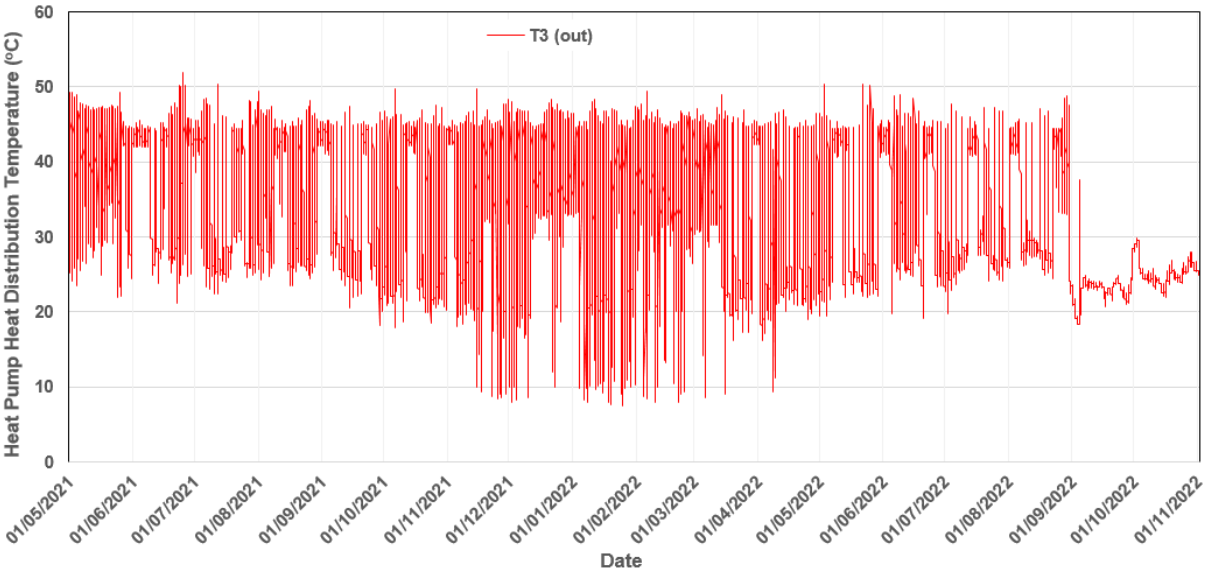


Figure 30. Heat pump heating energy distribution line outlet temperature

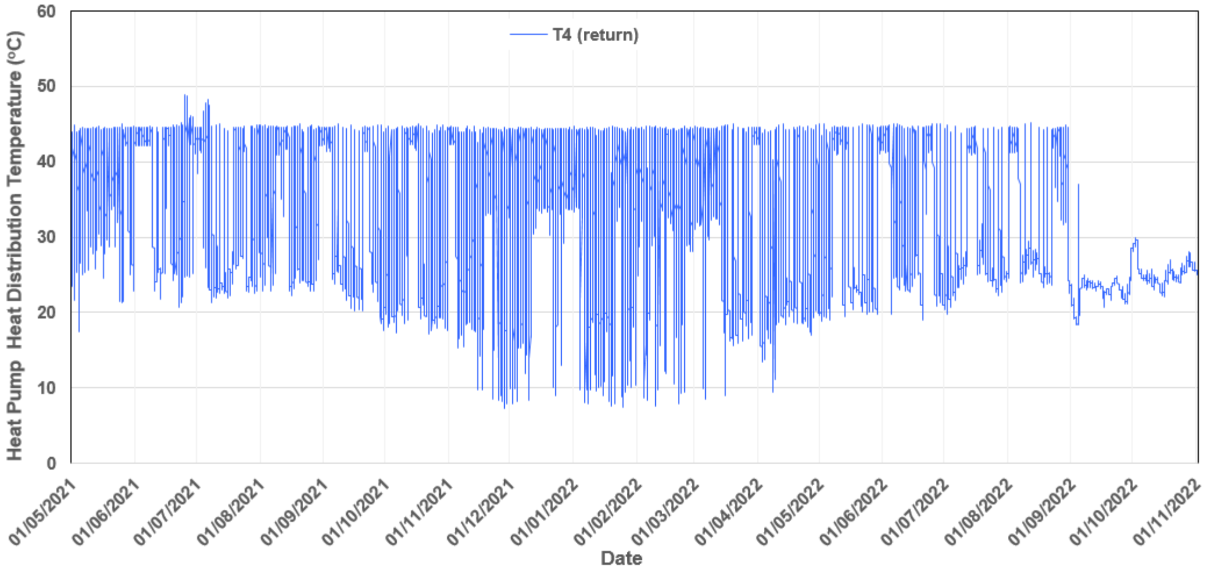


**Figure 31. Heat pump heating energy distribution line return temperature**

The heating season contains four months from November to February, in which the total heating energy extracted from the boreholes (HM2) is calculated as 73486 kWh based on the measurements.

The heating energy used at site is 40576 kWh in total, where 39724 kWh is for heating the adjacent building (HM3) and 852 kWh for de-icing (HM1).

## 4.5 Economic Impact of Power Road® for De-icing

Around 852 kWh heating energy is used for de-icing through the winter period. However, the amount of salt required for de-icing couldn’t be calculated as the required data of salt requirement per unit area/length, total surface area or road length and number of icy/snowy days during the four months have not been provided.

The electricity consumption of heat pump for de-icing is 516 kWh, which is calculated based on the heat pump efficiency (COP=1.65) and total heating energy (852 kWh). The total heating cost of the de-icing via heat pump is calculated as £170. As a comparison, the same amount of heating demand requires consuming 80 $m^3$ of natural gas and the related cost is £87.

We have used the following data in undertaking these economic calculations:

- Electricity price (based on Bulb energy, 5% tax included, Nov 2022): 33.017 p/kWh
- Natural gas price (based on Bulb energy, 5% tax included, Nov 2022): 10.24 p/kWh
- 1 m3 Nat. Gas = 10.68 kWh
- 1 m3 Nat. Gas = 8250 kcal and efficiency 93%

## 4.6 Economic Impact of Power Road® for the Heating of Adjacent Buildings

The electricity consumption of heat pump to support the heating for buildings is approximated as 24075 kWh, which is calculated using the heat pump efficiency (COP=1.65) and total heating demand (39724 kWh). The total heating cost of the building via heat pump is calculated £7949.

Comparatively, the same amount of heating demand would be met by combusting 3719 $m^3$ of natural gas which will cost £4068. The parameters used for the above calculations are listed as follows:

- *Electricity price (based on Bulb energy, %5 tax included, Nov 2022): 33.017 p/kWh*
- *Natural gas price (based on Bulb energy, %5 tax included, Nov 2022): 10.24 p/kWh*
- *1 $m^3$ Nat. Gas = 10,68 kWh*
- *1 $m^3$ Nat. Gas = 8250 kcal and efficiency %93*

## 4.7 Environmental Impact of Power Road®

Compared with using gas boilers, using heat pumps is more environment friendly if they are powered by renewable energy. Normally, applying heat pump is more cost effective than gas boilers. However, the measured efficiency of the heat pumps in the Power Road® system is lower than the expected value (designed as 41 kW heating load in the manufacturer specification), which leads to a higher cost than consuming natural gas to meet thermal demands.

Utilization of heat pump instead of salt for de-icing needs further investigation and data input.

## 4.8 Conclusion

The expected measurement and monitoring data against the plans for the types of analysis that Cranfield University has committed to undertake is summarised in Table 3. All analysis was carried out for the time period when data was available, May 2021 to November 20220.

**Table 3. Summary of data provided and analysis performed**

| Expected measurement and monitoring data | Assessment |
|---|---|
| Measure and collect temperature data from geothermal reservoirs via sensors | 05/2021- 11/2022 |

| | |
|---|---|
| Physically investigate de-icing performance on trial sites | Not provided |
| Measure heating load of adjacent buildings (if they are connected to Power Road®) and collect data of heat supplied by heat pumps | Partially provided |
| **Planned analysis** | **Assessment** |
| Estimate the distribution of heat to road and adjacent building based on the available heat stored in underground | Completed for the available data |
| Estimate heat quantity and evaluate efficiency of transferred heat to de-icing and heating adjacent buildings | Completed for the available data |
| Evaluate coefficient of performance (COP) of heat pumps | Completed for the available data |
| Estimate the amount of salt and gas/oil avoidance for de-icing and heating, respectively | Completed for the available data |
| Estimate energy bills saving if the Power Road® is applied adjacent buildings | Completed for the available data |
| Estimate environmental impacts of Power Road® by avoiding the use of salt and heating buildings with gas/oil | Completed for the available data with some caveats |

In particular, if the following data is provided, the robustness of our environmental and economic calculations would be improved significantly:

- Number of icy/snowy days
- Amount of salt utilisation per $m^2$ or m of the surface
- Definition other efforts and energy to keep clear the Power Road surface
- Definition of building indoor conditions and utilization records

Additionally, the preliminary results show that the heat pump operations within the Power Road® system is not efficient with a summary of key results as follows:

- $COP_{heating}$: ~1.65
- $COP_{Carnot}$ : 7.2  (@ $T_{evp}$: 5°C, $T_{cond}$:50°C)
- Second Law efficiency of heat pump system: ~23%
- Adjacent building heating requires 24075 kWh of electricity and costs £7949 via heat pump
- The same heating demand for Adjacent building requires 3719 $m^{3\ of}$ natural gas and costs £4068 via gas boilers
- The de-icing heating requires 516 kWh of electricity and £170 via heat pump
- The same heating demand for de-icing requires 80 $m^3$ of natural gas and costs £87 via gas boilers

In conclusion, the heat pump system is less efficient than expected and the costs are higher than consuming natural gas when meeting the same amount of thermal demand. This is probably due to measurement errors which was raised with the installers on several occasions. Based on these calculations, this system does not offer value for money but closer examination of inconsistencies in data is strictly advised as there seem to be many measurement errors.

# 5 References

[1] H. Z. al Garni, A. Abubakar Mas'ud, M. A. Baseer, and M. A. M. Ramli, "Techno-economic optimization and sensitivity analysis of a PV/Wind/diesel/battery system in Saudi Arabia using a combined dispatch strategy," *Sustainable Energy Technologies and Assessments*, vol. 53, p. 102730, Oct. 2022, doi: 10.1016/J.SETA.2022.102730.

[2] S. Winder, "Applications," *Power Supplies for LED Driving*, pp. 289–299, Jan. 2017, doi: 10.1016/B978-0-08-100925-3.00017-3.

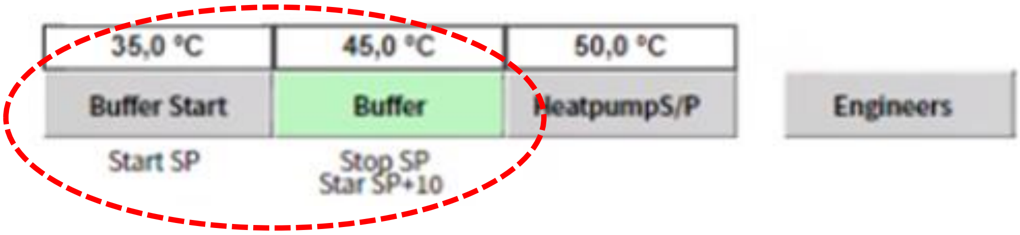
[3] Kensa Heat Pump Data Sheet (TIS - Evo Heat Pump Single – 5), https://www.kensaheatpumps.com/

[4] BS EN 14511 Air conditioners, liquid chilling packages and heat pumps for space heating and cooling and process chillers, with electrically driven compressors: Test Conditions

# 6 Appendix

For Power Road®, further analysis to explain temperature fluctuations at graphs especially T10, T3 etc is presented below.

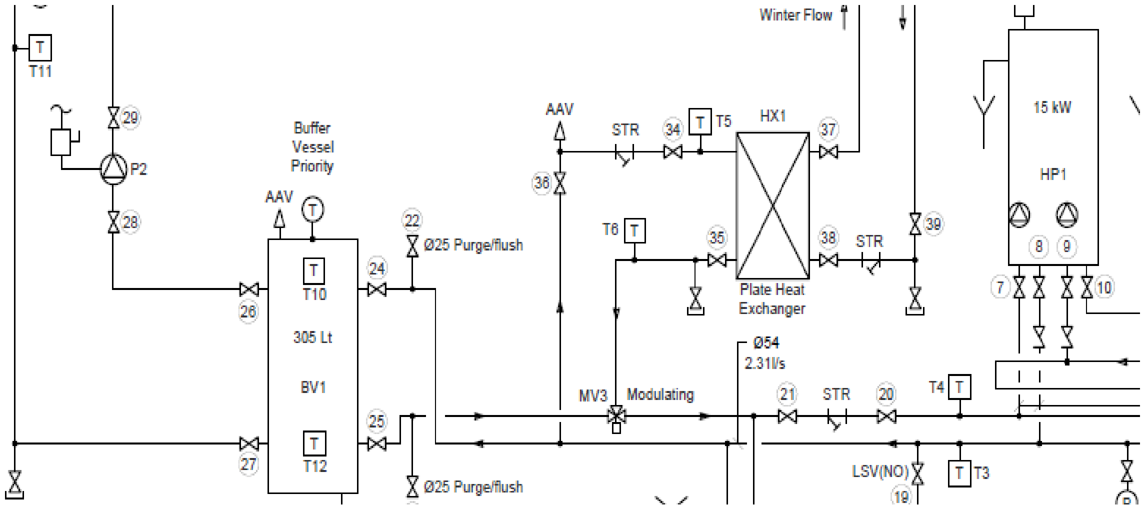
1. At T=35ºC buffer starts and T3 flows to the buffer
2. When the buffer stars T10=35ºC time is 14:15 (above figures)
3. At the same time (when buffer started) T3=22.4ºC
4. T10 (to the building) is affected from the T3 (output of HP) and decrease rapidly
5. After buffer start HP also start and send heated fluid to the buffer then T3 and T10 temperature starts increasing
6. At T=45ºC the buffer stops therefore T10 starts decrease
7. The graphs above given for 3 days (Nov 10th to 13th) at the highest fluctuation

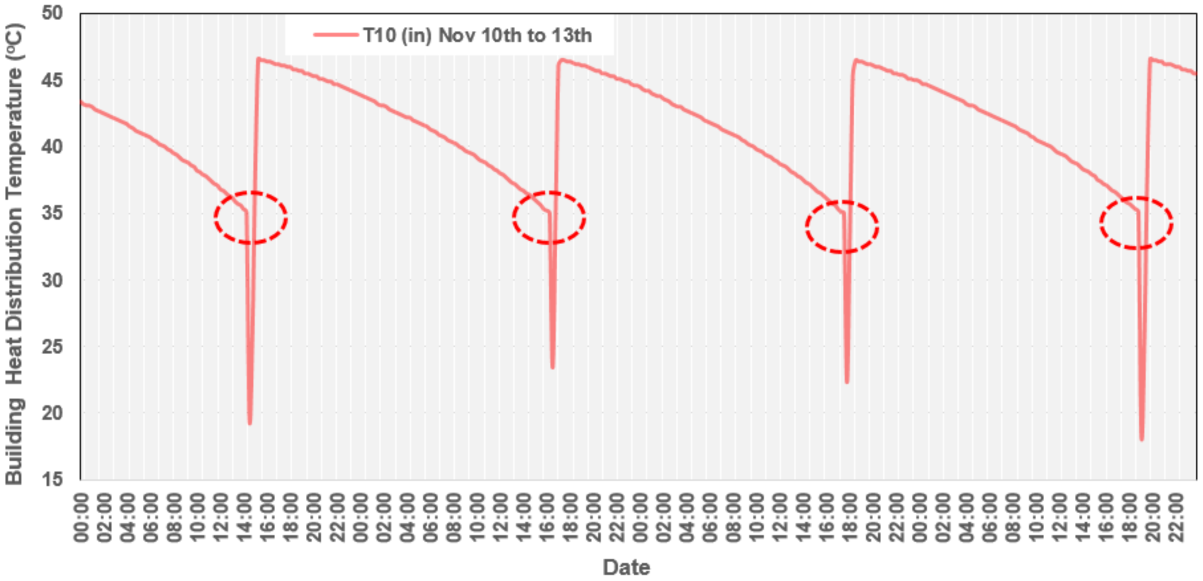


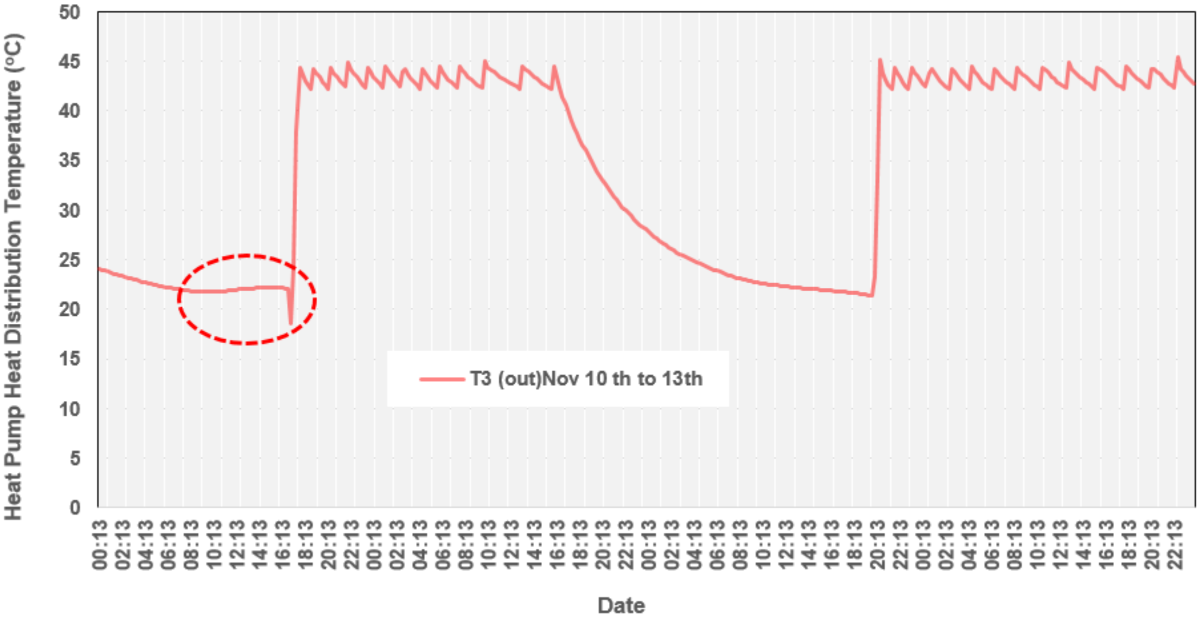
35,0 °C

45,0 °C

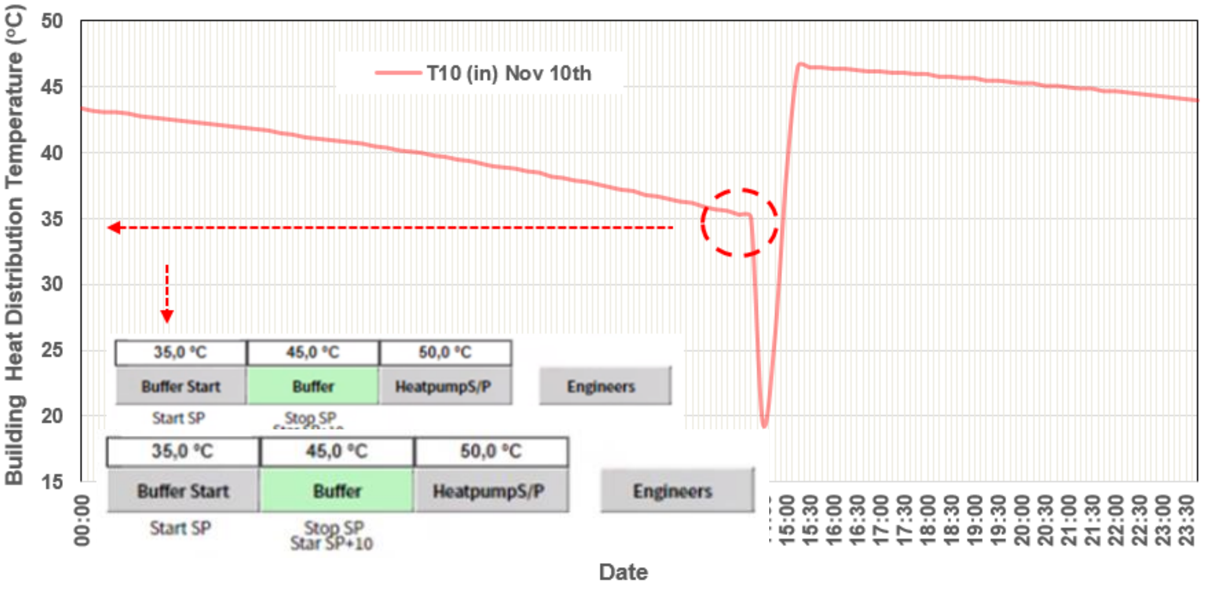
50,0 °C







As seen below, the lowest temperature for T3 is ~19ºC also for T10. On the other hand, there may be a synchronisation error of measurements at T3 and T10 which needs to be checked further.


Building Heat Distribution Temperature (°C)
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40
35
30
25
20
15
T10 (in) Nov 10th
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45,0 °C
50,0 °C
Buffer Start
Buffer
HeatpumpS/P
Engineers
Start SP
Stop SP
Star SP+10
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15:30
16:00
16:30
17:00
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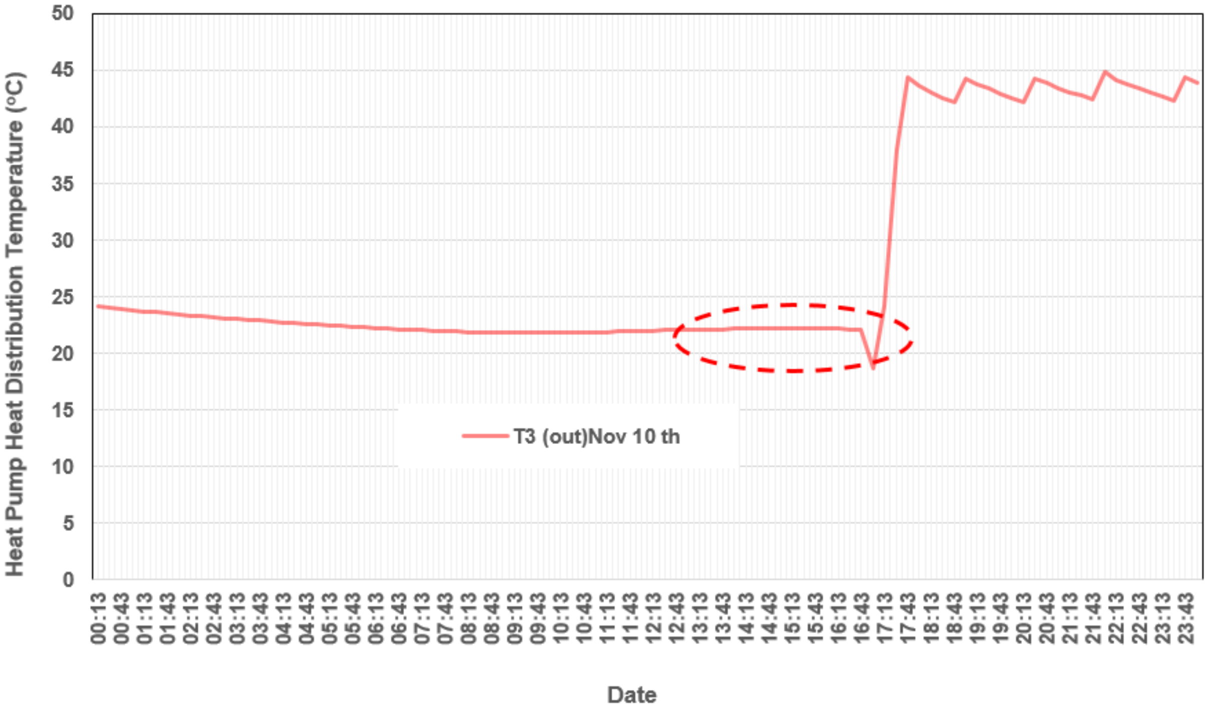
Date


Heat Pump Heat Distribution Temperature (°C)
50
45
40
35
30
25
20
15
10
5
0
T3 (out)Nov 10 th
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00:43
01:13
01:43
02:13
02:43
03:13
03:43
04:13
04:43
05:13
05:43
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