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Reducing Environmental Footprints of Buildings Heating, Cooling and Ventilation by More Efficient Use of Energy and Supply from Renewables

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Greenhouse Gas Footprint minimisation and security of energy supply are important components of sustainability. Achieving these can be offered by the combination of technologies demonstrated by the Horizon 2020 project RESHeat presented in this work. The technology captures, stores and uses solar energy efficiently, employing Photovoltaic-Thermal and Thermal Solar collectors combined with underground heat storage and heat pumps. As a result, the proposed system has been shown to be capable of catering for more than 90 % of the energy demands of residential buildings and bears the potential to reduce more than 80 % of the Greenhouse Gas Footprint compared with the mode of using grid power only. Future project activities will focus on completing the technology demonstrations and a thorough sustainability evaluation – including further footprints and economic viability.

1. Introduction

There is a well-proven need for the reduction of GHG Footprint and the Footprints of other health-impacting emissions, including SO_x, O_3, VOC, and PMs – and serious reduction targets (EEA, 2021) have been instituted. The residential sector and specifically buildings, contribute to the overall energy demands of about 36 % in the United States (LLNL, 2022) and 26 % in the EU (Eurostat, 2020). This is directly related to the emission releases. Buildings can increase the inherent efficiency of energy use, combined with the use of renewable energy sources in different ways. For buildings, the most appropriate renewable energy supply comes from solar energy capture and the use of heat pumps for geothermal use.
The time of high availability of solar energy in the summer and daytime is different from the time of highest energy demands in residential buildings – typically in the winter and evening hours. This mismatch on the daily scale can be solved by buffer tanks, while the seasonal imbalance is handled using Seasonal Thermal Energy Storage (STES) (Ocłoń, 2021). Another part of successfully solving the problem of solar energy capture and supply is to make the capture and conversion processes as efficient as possible and provide the captured energy in amounts sufficient to meet the user demands - especially during peak periods. The solar energy capture has to be maximised, followed by efficient conversion to electrical power. Within this context, solar tracking systems are used to maximise the panel exposure to solar radiation. However, increased exposure and the higher value of solar energy influx to the panels increase the temperature of PV panels and decrease their electrical conversion efficiency. A cooling system is typically applied to alleviate the issue (Ocłoń et al., 2020), restoring the efficiency of the PV modules. Such a modification brings the double benefit of increasing the power generation and the possibility of using the captured heat as a secondary useful output. The additional heat flow, with temperature 35 – 40 °C in Polish conditions, may be used, e.g., for preliminary heating of Domestic Hot Water (DHW). However, can be uneconomic due to the necessity of further heating the water to 60 – 80 °C using other energy sources. The use of low-temperature heat directly or for ground heat regeneration as the

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lower-temperature heat source of a heat pump may be an economically and environmentally attractive solution, improving the efficiency of heat pumps (Kozak-Jagieła, 2021).

Solar thermal and PVT modules have been developed to the point of offering reasonable conversion efficiency and ever-decreasing costs (Ocłoń, 2021). This bears the promise of solving two significant problems of contemporary societies – environmental issues, the high cost of energy supply, and minimising the risk of supply interruption. RESHeat is a demonstration and innovation project. Its novelty, compared with previous projects, is in the demonstration of the use of PVT panels and solar thermal panels – both types with sun tracking, combined with short-term heat storage and ground heat regeneration for use by heat pumps.

However, the scope of the potential environmental benefit and the economic performance of the RESHeat system has not been quantified in the new situation since the beginning of 2022. The current paper reviews the initial outcomes of the RESHeat project, the energy, environmental and monetary performance potentials, and the possible benefits of integrating RESHeat technology with various processing and residential energy systems. The energy substitution, emission reduction potential and preliminary cash-flow performance are also analysed.

2. RESHeat project presentation and applications

The RESHeat project started in December 2020 (Ocłoń, 2020). This is a Horizon 2020 project which is part of the sub-programme “Societal Challenges - Secure, clean and efficient energy”. The project goal is to develop a system for the use of solar energy as the primary renewable energy source within the context of buildings. While the emphasis of the idea is on residential buildings, the technology is applicable to a wider range of settings – including shopping centres, office and administrative buildings, hospitals, hotels, and restaurants. This has been shown from the perspective of Total Site Heat Integration (Varbanov et al., 2022). This section provides a review of the RESHeat system mapping its features to the issues they address, an evaluation of the emission reduction potential and an overview of the potential applications of the technology.

The project has demonstration facilities at several locations (Ocłoń, 2020): a municipal building in Cracow – Poland, a family-style house in Limanowa – Poland, and a site with a municipal building in Palombara Sabina – within the Metropolitan City of Rome, Italy. The panels are fitted on the roofs of the municipal buildings, while the family house site has the panels on separate stands on the ground close to the buildings.

2.1 RESHeat technology and main topology

As mentioned in the introduction, the ensemble of a PV panel and an added cooling system is referred to as a Photovoltaic-Thermal (PVT) Panel since its outputs are electrical power and heat flows. Sun tracking is a technique for adjusting the angle of solar panels (PV and thermal) that increases the exposure of the panel surface to sun rays and results in higher solar energy yield in the panels. The goal of sun tracking is to keep the surface of the panels perpendicular to the incident solar radiation. In the case of PV panels (Kozak-Jagieła, 2021), sun tracking is combined with a panel cooling system which achieves two simultaneous effects – increasing the efficiency of power generation by reducing the panel temperature and the generation of hot water, essentially providing a Combined Heat and Power (CHP) generation facility. There are several types of devices for sun tracking – including single-column designs and parallel console types. The power supply to the tracking mechanisms can be autonomous or auxiliary. The mechanism is linked to solar detection sensors, delivering continuous or stepping motion, tracking for all or part of the year, and tilt angle adjustment.

The selection and sizing of the system components are described in detail in (Ocłoń, 2021). The mathematical model of the combination of PVT panels and heat pumps is given in (Vallati et al., 2019).

The proposed system is illustrated in Figure 1. The main parts of the system are solar panels (PVT and solar thermal) with sun tracking, underground tanks for heat storage and regeneration, heat pump(s), piping, fluid pumps, and power electronics. The system is also fitted with on-site batteries and the overall operation of the electrical part of the system is managed by a control system. The piping and fluid pumps provide fluid circulation through the system. The power electronics – inverters, controllers, and grid connection, ensure the correct functioning of the electrical power system of the building.

Key components are the solar panels – PVT and thermal, with sun tracking. Figure 2 shows an example of sun-tracking PVT panel modules at one of the RESHeat demonstration sites in Poland. The backbone of the system are the PVT panels generating power and heat. In case the building has additional heating demands, the solar capture field can be complemented with solar thermal panels integrated into the heat carrier fluid circuit with the PVT panels. Another option, if the Power-to-Heat Ratio of the building energy remands is higher, is to install a combination of PVT and simple PV panels or to design the system with PVT panels and import the remaining power deficit from the central grid. In summary, on the solar capture field, sun tracking, PV panel cooling, and CHP generation result in a substantial increase – up to 45 % (Thorat et al., 2017) in the efficiency of solar energy capture and utilisation, which is the main reason for employing this combination of design features. The effect of co-generation of power and heat leads to a potentially much higher utilisation rate of the captured solar heat.

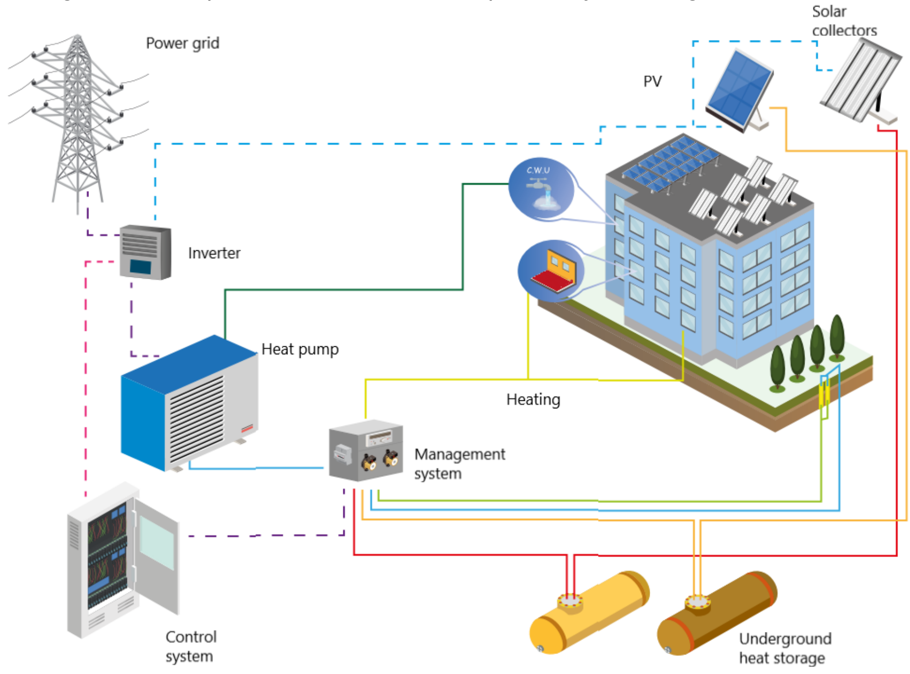

Figure 1: RESHeat system parts and topology

Figure 2: Sun-tracking modules of PVT panels (original image from the RESHeat project demo sites)

Another essential element of the proposed system is to enable heat storage and delayed reuse in periods without sunshine, as well as on a seasonal basis. The combination of two storage approaches is used as follows:

- Short-term heat storage is provided with an insulated fluid (water) tank. This caters for the short-term (hourly and daily) variations of the balance between solar heat supply and heat demands.
- Long-term heat storage is provided by combining Ground-Source Heat Pumps (GSHP) with seasonal regeneration of the ground heat. The latter is made possible by installing a second fluid tank in the ground under the building, which is not insulated. This arrangement allows the gradual accumulation of heat in the ground around the non-insulated tank during summer periods. The accumulated ground heat is then used by the GSHP during the cold months of the winter.

2.2 Potential for emission reduction

The RESHeat system intended for the demonstration sites in Poland and Italy has been designed and sized, and the designs have also been evaluated using rigorous simulations with TRNSYS (2019) and in-house software being developed as part of the project. The simulation results (Figure 3) show that the overall energy demands of the test building were served by the RESHeat system with the two heat storage tanks and the heat pump at the rate of 90 %.

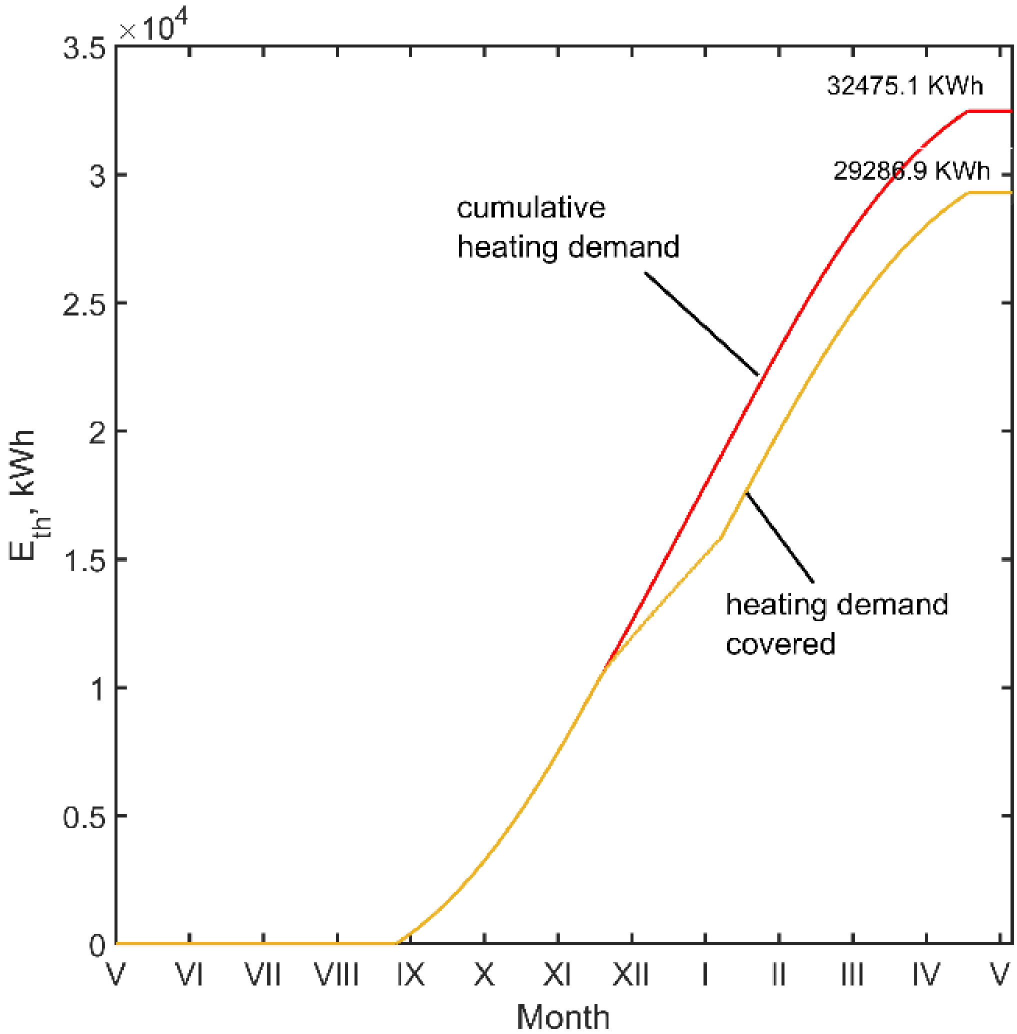

Figure 3: Cumulative energy flows for the test building – energy demands (upper curve) and RESHeat system supply (lower curve) for a 1 y cycle

Table 1: Potential GHG emission reduction

		Germany	Poland
Total house consumption	kWh/y	32,475	
RESHeat covered supply	kWh/y	29,290	
Grid power	kWh/y	3,185	
Share covered	%	90.19	
Grid GHG intensity	kg CO_2/kWh	0.350 (STATISTA, 2022a)	0.736 (STATISTA, 2022b)
PV GHG intensity (Müller et al., 2021)	kg CO_2/kWh	0.029	
Embodied GHG emissions from grid import	kg CO_2/y	1,115	2,344
Life Cycle GHG emissions from the RESHeat usage	kg CO_2/y	849	
Total GHG emissions from the building	kg CO_2/y	1,964	3,194
GHG reduction	%	83	87

For the test building with a total annual energy demand of 32,475 kWh/y, a calculation has been performed of the potential GHG emission reduction from using the RESHeat system. It considers the estimation of the perfornance for the Polish conditions and extrapolates what would be the performance of a similar house for German conditions (a similar climate).

The result is summarised in Table 1. The average grid power intensities for Germany and Poland in 2021 were taken from the Statista website. On the other hand, since reliable, precise estimates of the RESHeat installation are not yet available (these measurements are ongoing as of October 2022), GHG emission estimates for simple PV panels were taken (Müller et al., 2021). It is worth noting that the RESHeat GHG emissions over the life cycle are expected to be similar or even lower since the RESHeat system offers both power and heat generation compared with the power generation only of simple PV panels. In summary, replacing approximately 90 % of the building energy demands with solar energy has the potential to reduce GHG emissions (footprint) by more than 80 % compared with the situation of powering the entire buildings from the grid. It should be noted that the GHG savings for the German conditions for the year 2022 would be similar to those in Poland since the natural gas supply to Germany has seen a sharp decline, and the GHG intensity of the German power grid started approaching that of the Polish grid.

While the GHG savings potential from installing and operating the RESHeat system is remarkably high, it has been well-proven for other energy applications – including the use of renewable energy, that other footprints need to be considered. According to the comprehensive book on environmental and sustainability evaluation (Klemeš, 2015), there are other footprints that need to be taken into account. These include Water Footprint, particulates, as well as social-related footprints.

2.3 Integrating RESHeat with industrial processes and residential applications

Another way of maximising the impact potential of the RESHeat project is to propagate the idea of supplying renewable energy to other applications. Such applications need mainly available free areas for installing the PVT and solar thermal panels. The installation of the heat pumps or the storage tanks is optional – depending on the energy needs of the applications. Considering the moderate temperature of the waste heat generated by the PVT panels (35 - 65 ºC) and the potential upgrade to a maximum of 85 - 90 ºC using solar thermal collectors installed in parallel or in a sequence, potentially beneficial applications can be:

- Commercial centres and office buildings
- Hospitals, hotels and restaurants
- Food industry – including poultry/meat, vegetable processing or breweries, sugar plants
- Pulp-and-paper – with some further upgrades of the temperature to allow serving evaporators

A common feature of the enumerated candidates is the need for large amounts of heat below 150 ºC and the potential availability of free area on the roofs of the buildings and in the yards of the corresponding industrial sites.

3. Conclusions

This article has provided an overview of the key features of the technology offered by the RESHeat project for solar energy harvesting, storage and use for residential buildings. The key features of the proposed system have been analysed and mapped to the issues with renewable solar energy use that they are addressing.

The system simulations provide proof of the concept and indicate that it is possible to cover up to 90 % of the energy needs of a family house using the RESHeat technology. It has been shown that the proposed combination of sun tracking, PVT solar panels, buffer tanks, underground heat storage and heat pumps are capable of significant substitution of the building energy demands – of up to 90 %. This maps to GHG Footprint reduction potential above 80 and close to 90 %. Future work on this project will involve the completion of the demonstration site measurements, as well as the elimination of the limitations of the current state of development. This involves a sustainability evaluation of the system and the conclusion of replication agreements. The sustainability evaluation will be based on the Life Cycle framework and should involve further footprints beyond GHG – especially Water Footprint. The economic viability of the system has to be also assessed and demonstrated.

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