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Solar and geothermal energy for low-carbon space heating and energy independence.

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Abstract

In developed countries, space heating is highly dependent on fossil fuels consumption. Also, the non-renewable fuels combustion emits CO_2 which is claimed to impact the most on greenhouse effect. The utilization of Renewable Energy Sources (RES) for space heating, instead of fossil fuels, has been found to be feasible for systems' greater energy independence and reduction in CO_2 emissions. Solar Assisted Ground Source Heat Pump (SAGSHP) systems are a promising technology which can be used to accomplish the above framed target.

A mathematic model of a SAGSHP system was built and a parametric analysis for Birmingham which is a city located in the UK's West Midlands was conducted. Two scenarios based on two different dwellings were investigated, the one was a house recently erected and the other was a refurbished house. As regards the new house, simulation results showed that the utilized energy for space heating and Domestic Hot Water (DHW) can vary from 33% up to 73% RES dependent and, at the same time, electricity generation can be 2.21 times higher than the system's demand. As regards the energy renovated dwelling, the RES contribution to the delivered heat was found to be between the 33% and 63%, while the electricity generation did not result in any surplus energy from the consumed. Finally, by making use of SAGSHP system instead of a natural Gas boiler, the reduction of CO_2 emissions was found to be between 300kg/year and 2,170kg/year for the new building and from 245kg/year up to 3,221kg/year for the refurbished house, respectively. In both cases, SAGSHP systems proved to be a feasible practice for greater energy independence from non-renewable energy sources with substantial positive impact on the greenhouse gasses emissions.

Nomenclature

Subscripts	
BHE	Borehole Heat Exchanger
FPC	Flat Plate Collector
GHE	Geothermal Heat Exchanger
GSHP	Ground Source Heat Pump
NG	Natural Gas
NGB	Natural Gas Boiler
PVT	Photovoltaic and Thermal Collector
SAGSHP	Solar Assisted Ground Source Heat Pump
Nomenclature	
Q	Heat (kWh)
E	Electricity (kWh)

Introduction

In the European Union (EU), the domestic sector consumes 25.4% (EUROSTAT, 2015) of the total energy needs, while 64.7% of this amount is consumed for space heating and 14.5% for DHW. Over the past decades, the reduction on the energy used in domestic sector for space heating has been a major focus of researchers, governments and intergovernmental organizations, such as the United Nations (UN), with regards to the SDG 7 target. The need for more sustainable space heating systems with more dependence on Renewable Energy Sources (RES) and less on fossil fuels is important aiming at more environmentally friendly energy generation which can be accessible by all citizens.

The Solar Assisted Ground Source Heat Pump (SAGSHP) systems can utilize solar and geothermal energy in order to supply space heat and DHW to a building. A lot of effort has been made in order to investigate the SAGSHP systems feasibility. Therefore, SAGSHP systems like this of (Wang, Zheng, Zhang, Zhang, & Yang, 2010) have been built and investigated in real life conditions. The system is installed in China and after two years operation report a Heat Pump's COP of 4.29. Another investigated project was installed in France (Trillat-Berdal, Souyri, & Fraisse, 2006), with its Heat Pump's calculated COP at 3.75 after a year. Moreover, SAGSHP systems were found to be a promising alternative choice for space heating systems in houses which are about to be refurbished. With projects like this of (Nicholson-Cole, 2012a), (Nicholson-Cole, 2012b) which illustrates how conventional Ground Source Heat Pump (GSHP) systems with unbalanced soil temperature can be transformed to a solar assisted one and improve the system's COP from 2.6 to 4.4.

Almost all SAGSHP systems in existing literature have been found to be comprised by different kind of components. For solar energy harvesting, Flat Plate Collectors (FPC) and Photovoltaic-Thermal (PVT) collectors are among the most efficient options. At the same time, for the geothermal part, U-type Borehole Heat Exchangers (U-BHE) is the dominant choice with the very shallow Geothermal Heat Exchanger (GHE) to be avoided due to their highly influence from ambient conditions. Nevertheless, systems equipped with PVTs can cogenerate heat and electricity simultaneously and that is an advantage against conventional solar collectors which are restricted to provide only heat. Therefore, the PVT option has been attractive for SAGSHP systems and installations like (Bertram, Glembin, & Rockendorf, 2012), (Bateson, 2014) and the one which described by (Naranjo-Mendoza, Greenough, & Wright, 2018) justify the interesting for this solution.

The SAGSHP systems' feasibility and parametric analysis is mainly function of the location, systems interconnection, control and components selection. As a multi-objective system, the design can be very complex, therefore computer-based simulations are recommended due to low capital investment and flexibility in investigated scenarios. In this work, a validated via experimental data mathematic model of a SAGSHP system has been created with TRNSYS (Solar Energy Laboratory, 2012). The built model was utilised in order to conduct parametric analysis for a system placed in Birmingham. The proposed SAGSHP system is consisted of PVT collectors and a novel very shallow BHE field. Furthermore, two types of single-family residences were investigated, a newly erected one, according to the L1A regulation for new domestic building, and a refurbished one based on L2A for energy renovated dwellings. Both building scenarios were found to be environmental and energetically feasible for the chosen location.

Methodology

System summary

An experiment of a PVT-based SAGSHP has been conducted by De Montfort University (DMU). The investigated experimental system combines PVTs with a novel shallow GHE and details about the aforementioned project can be found in (Naranjo-Mendoza et al., 2018). From the experimental procedure, data were used to analyse the system's operation and a SAGSHP validated mathematical model was created. Also, the model of PVT collector was based on further experimentation (Sakellariou & Axaopoulos, 2018) and as for the Heat Pump's model, performance data according to the EN 14511 standard, from a well-known German maker were utilized. Both dwellings, the new and the refurbished one, were built by employing the TYPE 56 on TRNSYS. In the new and retrofitted house, the underfloor space heating system was chosen as the heating mean.

In both houses, the new and the refurbished one, their occupied area is set at 120m^2. The parameters which characterize the buildings energy efficiency are listed in Table 1. Also, all windows are made from PVC double-glazing with overall U-value of 1.27W/m^{2}K and the openings to walls average ratio is 0.138. Furthermore, the DHW is set to 140L per day at 50^{o}C, which is a substantial quantity for a four-member family. The annual demand for space heating was calculated at 3,522kWh$_{th}$ per year for the new house and at 9,741kWh$_{th}$ for the refurbished one accordingly. Regarding the Heat Pumps capacity, a 3kW$_{th}$ was chosen for the new house and a 4.8kW$_{th}$ for the retrofitted. Finally, the DHW energy needs were estimated at 2,528kWh$_{th}$ per year for both cases.

House type	Floor U-Value W/m^{2}K	Wall U-Value W/m^{2}K	Roof U-Value W/m^{2}K	Air Changes per Hour (ACH)
New Dwelling L1A	0.130	0.174	0.123	Set to 0.2 due to infiltration and 0.8 from mech-ventilation
Refurbished Dwelling L1B	0.250	0.288	0.175	Set to 1 ACH

Table 1. Dwellings thermal parameters.

The systems' main operation modes are shown in Table 2. Moreover, the electricity generated by PVTs is always injected into the electric distribution grid, while the power inverters' efficiency together with Joule losses on the cables are summarized to a total 10% reduction.

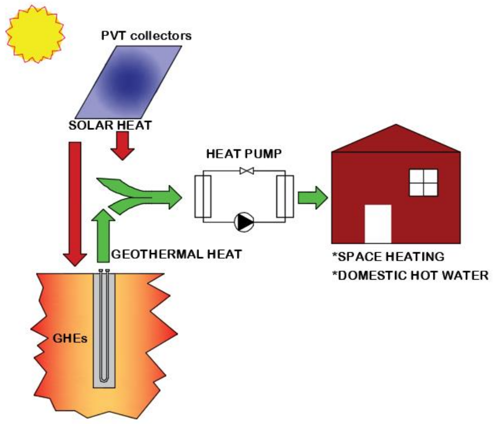
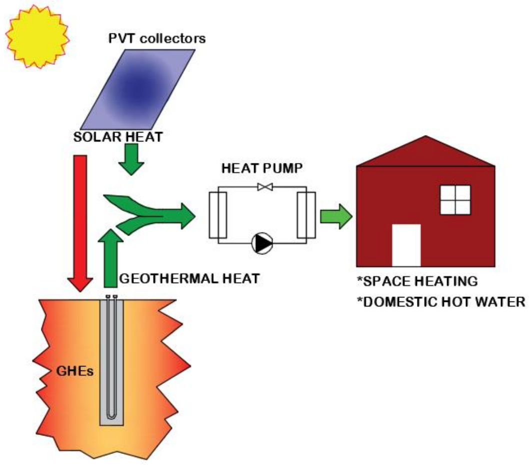
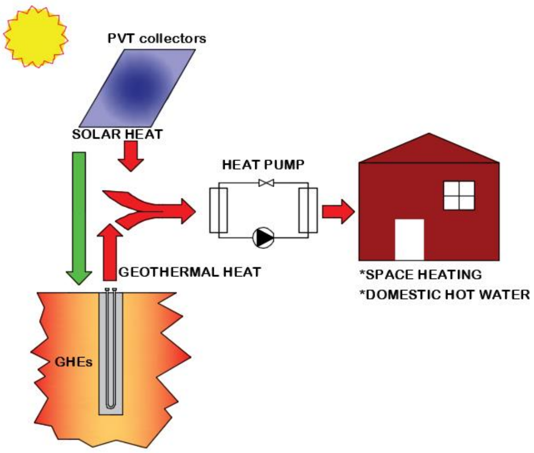
<table>
<tr><th>Schematic representation (heat flow)</th><th>Operation mode - Description</th></tr>
<tr><td>
</td><td>1. Heat pump operates and provides heat without solar heat contribution (no adequate irradiance).</td></tr>
<tr><td>
</td><td>2. Heat pump operates and provides heat with solar heat contribution via the GHE. (substantial irradiance in order to contribute in the house heating).</td></tr>
<tr><td>
</td><td>3. Solar heat recharging the soil (no need for space heating or DHW, thus the heat from the solar system is stored in the soil).</td></tr>
</table>

Table 2. Systems main operation modes.

Parametric Analysis

Regarding the parametric analysis, it is conducted by changing the quantity of PVTs and the size of the GHE at every simulation. In more details, PVTs are set to vary from 0 to 20 by pairs of 4 PVTs in series hydraulically connected. For every PVTs configuration, the GHE is going to take 4 different sizes of 16. 24, 32 and 40 short BHEs at 1.5m long. Therefore, for each dwelling type, 24 simulations of 10-years period with simulation time step set to 1h have been executed. Also, the GHE is modelled to be installed beneath the house for the new dwelling, while for the energy renovated one the GHE assumed to be exposed and buried 0.5m below the ground.

The Renewable Energy Fraction (REF) which is the heat supplied by RES as ration of the total delivered heat to the house (Fig. 1) is calculated for each simulation. Practically for the current system the REF can be calculated by dividing the heat added to the systems by the heat pump's evaporator with the delivered (eq.1). In other words, with the REF the contribution of the RES to the delivered heat is indicated. Furthermore, the REF can hold values from 0 to 1, with the meaning for zero to stand for no contribution at all of renewables on the heat load, while one shows a system running 100% from renewable heat. Lastly, it is practical to explain that the delivered heat on the load breaks down to three parts (Fig. 1), the heat absorbed by the Heat Pump, which is solar and geothermal heat, the energy added to the systems by the Heat Pump's compressor and the Auxiliary energy, if such is required.

$$REF = \frac{\sum Q_{HP-evaporator\,(1)}}{\sum Q_{delivered\,(1+2+3)}} \quad (1)$$

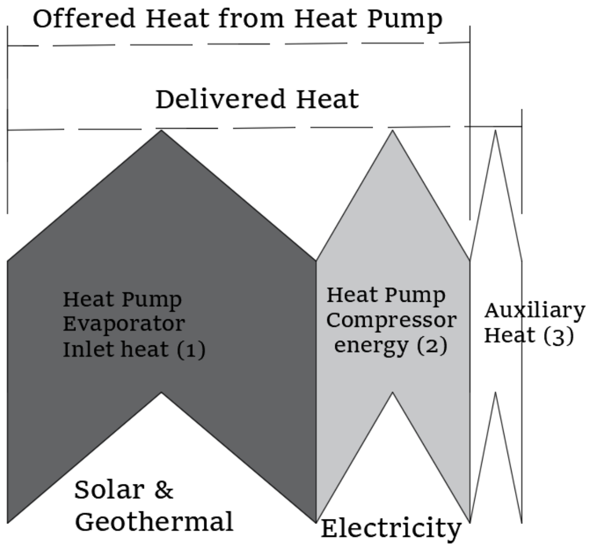


Fig. 1. Definition of the Delivered and Offered heat.

Accordingly, the Electricity Fraction (EF) is the ration of the electricity generated by PVTs divided by the consumed energy on the system (eq.2). The consumed energy consists of the electricity required for Heat Pump's compressor, the consumption of the circulation pumps and the consumption of the mechanical ventilation system. Contrary to the REF, the EF can be greater that one because generated electricity is directly offered to the grid and is not constrained by the consumption. For the investigated system, a net energy balance between the injected to the grid and consumed energy is assumed.

$$EF = \frac{\sum E_{generated}}{\sum E_{consumed}} \quad (2)$$

With regard to the system's environmental impact, the reduction of CO_2 emissions is investigated. The comparison is carried out by considering the proposed SAGSHP system against a Natural Gas Boiler (NGB). Regarding the NGB, it is assumed that it has to be designed to deliver the same amount of offered heat (portions 1 and 2 in Fig. 1) as the SAGSHP systems in every investigated scenario. In other words, the offered heat from the Heat Pump is going to be replaced by Natural Gas (NG) consumption. Furthermore, the NGB has average energy efficiency of 88% and is capable to provide space heat at the same low temperature as the SAGSHP does, at the underfloor heating system.

The comparison, regarding the environmental impact between the two systems, is going to take place by subtracting the released CO_2 from the combusted NG to the amount which emitted by the SAGSHP system. Nevertheless, the offered heat by SAGSHP systems is comprised by the REF and energy added by the Heat Pump's compressor. Therefore, the CO_2 emissions for SAGSHP system are caused only by electricity because solar and geothermal heat have zero emissions. All the above-mentioned calculations for CO_2 emissions are described by equation 3 to 5, with the conversion factors to be 0.20399 $kgCO_2/kWh$ for NG and 0.28088 $kgCO_2/kWh$ for electricity (UK-Gov, 2018) . Lastly, the auxiliary heat is a common portion in both cases and thus does not considered on the comparison.

$$CO_{2\_(balance)} = CO_{2\_(NG)} - CO_{2\_(electricity)} \quad (3)$$

With

$$CO_{2\_(NG)} = \frac{\sum[Q_{delivered}] \cdot 0.20399}{0.88} \quad (4)$$

And

$$CO_{2\_(electircity)} = \sum[E_{consumed} - E_{generated}] \cdot 0.28022 \quad (5)$$

Results

Simulations were conducted for a 10-year period with 1-hour simulation time step, but for illustrative convenience mean annual values are used. Also, all discussed parameters such as the generated electricity and the consumed heat were found to vary slightly from year to year during the simulation.

Based on equations 1 and 2, the REF and the EF have been estimated and illustrated in Fig. 2 and Fig. 3 for the new dwelling and the refurbished one, respectively. The REF is the portion of the total delivered energy, which has been fulfilled by solar and geothermal heat. In the same way, EF indicates the fraction of the consumed electricity, which has been provided by PVTs generation.

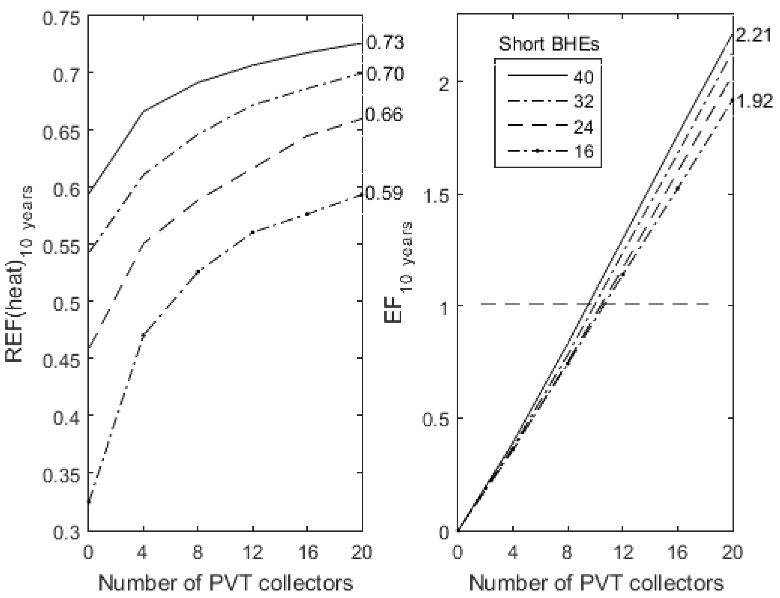


Fig. 2. REF and EF for the newly erected house as function of BHE size and PVTs quantity.

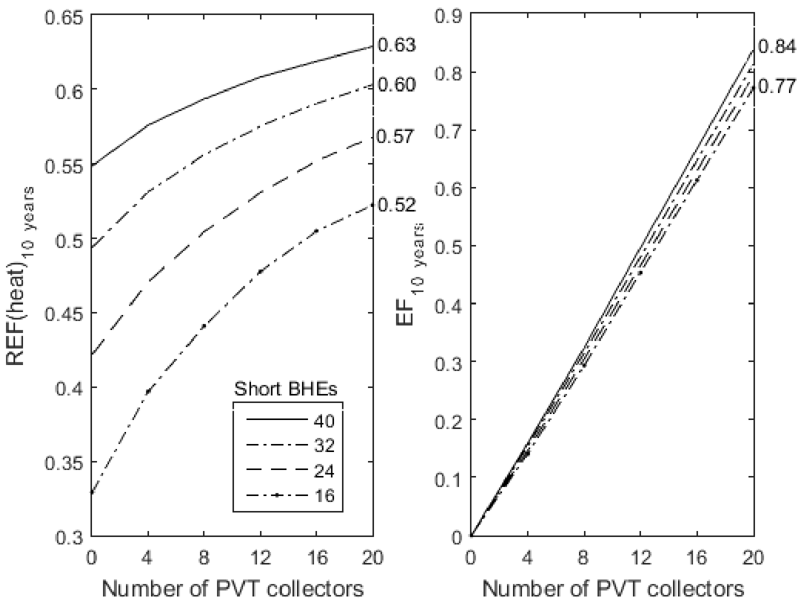


Fig. 3 REF and EF for the energy renovated house as function of BHE size and PVTs quantity.

The comparison between the SAGSHP system against the one replaced by NGB is taking place in Fig. 4 and Fig. 5, for the new and the refurbished house, accordingly. In more details, the reduction of CO_2 emissions for delivered heat is estimated by assuming that the equal amount of the Heat Pump's offered heat is replaced by NGB production (eq.4). Also, we have to bear in mind that negative emission gives a positive impact while negative are an actual released amount. In the investigated SAGSHP system, the Heat Pump's delivered heat is comprised by the renewable energy absorbed in evaporator and the compressor's consumed electricity. Also, the CO_2 released due to electricity consumption is based on equation 5, which indicates that by using PVTs' generation the CO_2 emissions can be decreased. Nevertheless, the electricity which is required by the system to operate is the addition of the portion consumed by the compressor and the parasitic energy.

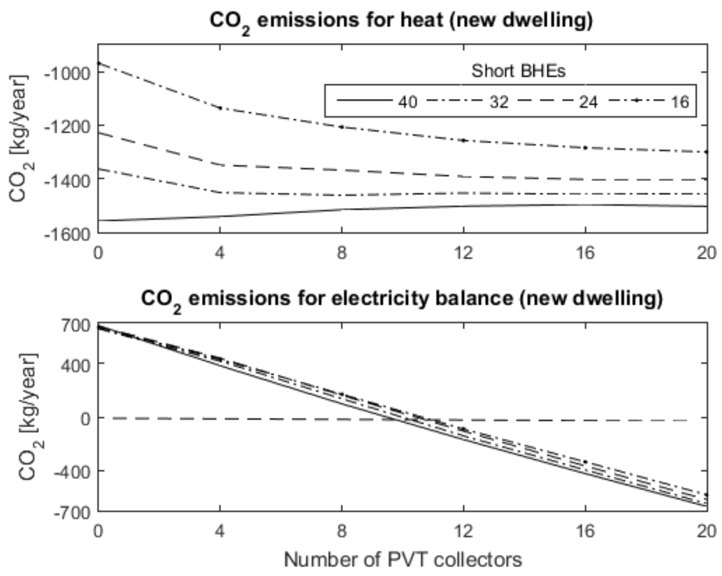


Fig. 4. CO_2 emissions from the heat delivered by SAGSHP systems against the NGB (eq.4) and the reduction of emissions by the electricity balance (eq.5), for the newly erected house.

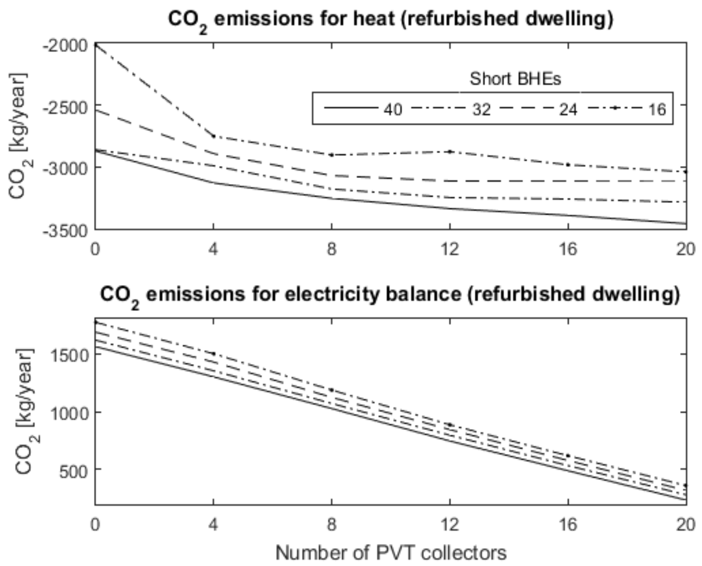


Fig. 5. CO_2 emissions from the heat delivered by SAGSHP systems against the NGB (eq.4) and the reduction of emissions by the electricity balance (eq.5), for the refurbished house.

Finally, the balance of the CO_2 emission between the SAGSHP and the NGB is shown by Fig. 6 for both dwelling scenarios. The CO_2 emissions, in both cases, have been estimated with equation 3, by considering the NGB's energy efficiency and the PVT's electrical efficiency.

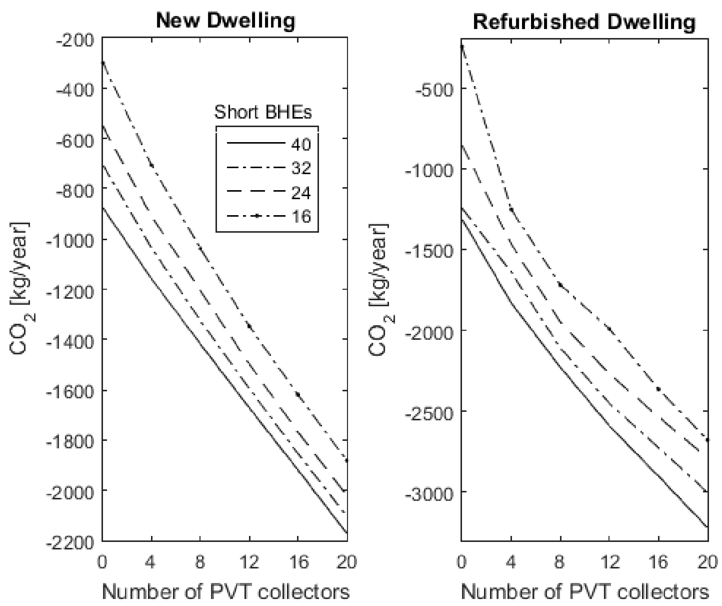


Fig. 6. Total CO_2 emissions decrease by utilizing the proposed SAGSHP systems against the NGB (eq.3). The comparison is for both dwellings and is illustrated as function BHE size and PVTs quantity installed.

Discussion

Regarding the newly built dwelling, the SAGSHP system was found capable of covering the 33% to 73% (Fig. 2) of total heating needs by solar and geothermal energy. About the refurbished house, the SAGSHP system managed to provide 33% up to 63% (Fig. 3) of total heating demand by RES. Nevertheless, the total energy demand for the new house has been estimated at 6.05MWh/year and at 12.270MWh/year for the renovated accordingly. According to the above-mentioned results, the SAGSHP system paired with the renovated house has managed to harvest more heat that the one with the new dwelling. That can be justified with Fig. 7, which illustrates the solar and geothermal energy entering the system for both houses as function of GHE size and PVTs amount.

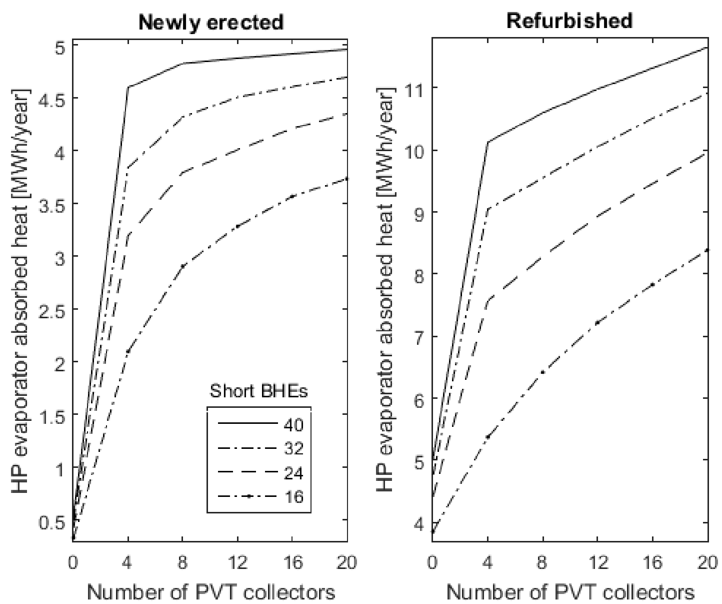


Fig. 7. Solar and Geothermal heat absorbed by the systems as function of GHE size and PVT amount.

Regarding the electricity balance in the systems, for the newly built house PVTs' electrical generation found capable to overproduce from the consumption after utilizing 10 collectors (Fig. 2). With the used PVT, which is rated at $235W_p$ and its electrical characteristics, the electricity generation was found to be 2.21 times higher than the consumption. Contrary to the newly erected house, the electricity consumed by the refurbished based system did not manage to generate more than the demand (Fig. 3). This is mainly caused by two reasons: firstly, the higher Heat Pump capacity (4.8 kW_{th}) for the renovated house against this of the new house (3.0 kW_{th}) and, secondly, the extensive operation hours in order to cover the more than two times higher heating demand.

According to Fig. 4 and Fig. 6, the newly built house gets negative CO_2 emissions in the whole of parametric analysis range. The total amount of CO_2 that is constrained from been released by using SAGSHP against NGB was found to vary from 300 $kgCO_2$/year to 2170 $kgCO_2$/year. Moreover, the electricity generation managed to decarbonize the emissions caused by the electricity consumption after using 10 PVTs collectors. By observing the CO_2 released by the heating part and the one which caused by the electricity (Fig. 4), the first amount was found to get high potentials to offer a positive environment impact. Finally, the parametric analysis, shown in Fig. 6 for the new house, illustrates that as the system get more PVTs to be installed and bigger GHE, the emissions decrease almost linearly.

Likewise the new house, the refurbished solution found to obtain a positive overall impact regarding the CO_2 emissions (Fig. 6). The discussed impact varies from 245 $kgCO_2$/year to 3221 $kgCO_2$/year with negative signed emission and is mainly due to heat decarbonization (Fig. 5). As it can be seen in (Fig. 5), the electricity did not manage to overcome the emission in the whole of PVT collector amount range. From results, the retrofit solution has achieved to decarbonize 1050 $kgCO_2$/year more that he newly erected house. Finally, the emissions reduction was found to follow the same linear trend with the new house, when the PVTs number increase or the BHE size become bigger (Fig. 6).

The analyzed SAGSHP systems are potential solutions in regard to the UK's targets for 100% electricity virtually made by RES by the 2050 (DECC, 2009). Also, the proposed systems, may assist on the UK's targets for reduction on CO_2 emissions and the energetically improvement of the existing houses. Based on the aforementioned two cases, the new market may offer employment opportunities during the construction, operation and maintenance.

Finally, the work's primary UN target is related to the energy sustainability (SDG7), but wen houses are equipped with RES the hole city may benefitted from that (SDG11). The reduction of CO_2 emissions and the replacement of fossil fuels with RES technologies improves the citizens energy accessibility. Moreover, the installed SAGSHP systems can operate as prototypes for students to learn about low-carbon housing. The education of young people about the environmental problems and the practical solutions makes them more aware regarding their way of thinking (SDG13).

Conclusion

In this study, a parametric analysis of a SAGSHP system with experimentally validated model was conducted. Based on findings, the proposed SAGSHP systems can be a viable solution for new low-rise dwellings or for retrofit. It may also be applicable to other building types. In more details, in the case of a nearly erected dwelling with the proposed SAGSHP system, the heating needs can be fulfilled by 33% up to 73%. Accordingly, the proposed system with the refurbished house was found capable of similar energy independence which starts at 33% and it can be as high as 63%.

Additionally, in the case of the new house, PVTs managed to overproduce from the system's consumption and export electricity to the electric distribution grid. In more details, the PVTs managed to generate 2.21 times more electricity than the consumed by installing 20 PVTs, while the system was found to get balanced by using 10 PVTs. The SAGSHP system based on the refurbished solution did not get any better than cover the 84% of the electricity demand. In the refurbished house, the EF can be increased by many ways, but the most straightforward is to increase the PVTs electrical capacity and, by that, to obtain higher generation.

Moreover, both investigated systems were found to get negative CO_2 emissions for the whole of parametric analysis range. The higher potential for CO_2 emissions reduction was obtained for the retrofitted house with 3,221 kgCO_2/year, as for the new one, the best value was 2,170 kgCO_2/year. It was observed that CO_2 emission drop linearly as the installed PVT capacity increased or the GHE became bigger. Finally, the energy and environmental sustainability can be achieved by the proposed system as it is proved be the case by this study. The aforementioned targets are among the EU's and UN's priorities which are to ensure access to affordable, reliable, sustainable and modern energy for all.

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