The Smart Combination of a Novel MicroCHP, PVs and Various Energy Storage Possibilities to Provide the Household Energy Needs All year Round

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Abstract. The problem of seasonal energy storage, where excess renewable energy in the summer months is stored to cater for the winter season, is an active topic being researched [1, 2]. The solution being proposed in this paper targets residential homes, and is the result of the development of a microCHP with integrated battery storage [3], all contained in the size of a home appliance. The microCHP will output a DC voltage that gives us the possibility of running certain loads directly. This work compliments previous work to provide an ideal Smart Home System with energy storage for operation with and without the grid [4]. Excess energy in the summer can either be used to add comfort to the home or can be injected in the grid, if this is available. In winter the PV panels will not generate enough and the microCHP can be used to top up the energy required. When combined with a heat pump, the microCHP can provide a very efficient way of heating the house. The authors here propose building material/water heat storage to reduce the size of the inverter/s and that of the chemical storage to provide the evening energy demand.

Keywords: Renewable energy · CHP · combined heat and power · energy storage · batteries · seasonal storage · residential · DC microgrid

INTRODUCTION

Since currently there is not a viable solution for seasonal storage of excess renewable energy for residential households, the authors have developed a microCHP with an integrated battery [3] in the size of a kitchen appliance to support the electricity and heat required during the winter seasons. The output of the microCHP is DC and this gives the possibility to run certain loads directly. This was a continuation of the work to provide an ideal Smart Home System with energy storage for operation with and without the grid [4].

It is very clear that in summer there is excess energy from an adequate number of PV panels which are today affordable. This can be ideally transferred directly to space
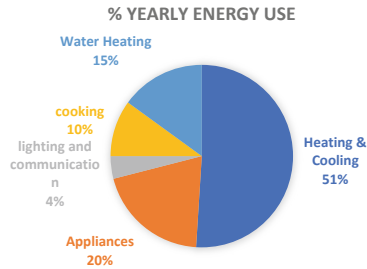
% YEARLY ENERGY USE

Water Heating
15%

cooking
10%

lighting and
communicatio
n
4%

Heating &
Cooling
51%

Appliances
20%

Fig. 1. % Energy used for different energy requirements in a house
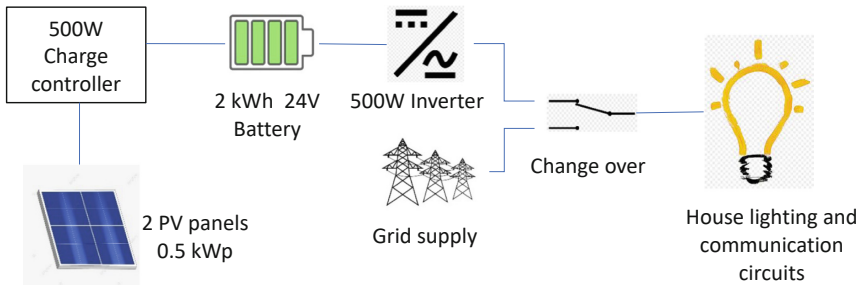
Fig. 2. PV and battery setup for powering the lighting and communication circuit all year round.

heating/ cooling during the sunny hours while charging a small chemical storage for other evening loads and for backup in the case of a power cut. Any additional energy can either be used to add comfort or can be injected in the grid if this is available. In winter the PV panels might not be enough and the microCHP can be used to top up the energy required. In combination with a heat pump, the microCHP can provide a very efficient way of heating the house. The authors propose building material / water heat storage to reduce the size of the inverter/s and that of the chemical storage to provide the evening energy demand.

ENERGY REQUIREMENTS IN A HOUSE

The yearly amount of energy that we use in a house is highly dependent on weather conditions, mainly due to heating and cooling requirements. The authors considered a dwelling of 150sqm with 4 persons– 2 adults and 2 children in a southern European area.

The pie chart of Fig. 1 shows the percentage energy used in this household. In colder countries, the chart will vary mainly due to the percentage of energy used for heating (and/or cooling) which typically increases to around 75%. The total amount of energy required is dictated mainly by how well the building is insulated. This lies in the range of 5 - 8 MWh /year in southern Europe and increases to 15 - 20 MWh/ year in Northern Europe.

The energy we use at home can be split into four categories;

1. *Lighting and Communication*
2. *Heating and Cooling of Space and Water*

3. *Cooking*
4. *Appliances*

1 Lighting and Communication

Lighting and communication are light loads and consume a very little percentage of the total energy / power demand. They are, however, needed most of the time, so backup in case of a power failure is essential and affordable.

Thanks to the development and progress in LED technology the energy and power demand of a 150msq dwelling with 3–4 people is estimated to be;

Summer	0.5 KWh / day
Winter	0.8 KWh / day

The authors have set up, in one of their houses in Malta, the configuration shown in Fig. 2. It consists of 2 PV panels which are used to charge a 2 kWh battery during the day. The battery discharges in the evening, supplying the lighting and communication circuits. This setup has been running for almost 2 years, independent of the grid. Although the design also caters for the possibility to switch to the grid once the battery is discharged to 30% SOC, this was never required so far. A third panel might be required if this is used in northern European countries.

2 Heating and Cooling

A substantial percentage of our energy demand is used for heating in winter and for cooling in summer. It has been shown by the authors in previous publications [4, 5] that while daily and short term storage (say 4 to 5 days) of energy from renewables is possible, seasonal storage is not. There are different ways of heating but there is only one way of cooling, and this is using a heat pump. The authors carried out an analysis of the various possibilities of heating and their related efficiency and costs.

2.1 Efficiency and Cost of Heating

The current global situation has caused a sharp increase in energy prices and has forced authorities to impose reductions, especially on the use of natural gas. In order to maintain existing comfort levels at home, the authors have analysed the efficiency and costs of heating in winter using commercially available technologies. For this analysis the tariffs below were used [6–8];

LPG	+9.0c/kWh
Electricity	+32.0c/kWh
CHP electrical feed in tariff	-26.7c/kWh
CHP electrical self-consumption	-8.0c/kWh

In order to meet new European restrictions on gas consumption, it is very important for the consumer to invest in the most favourable technology that will provide the cheapest and most efficient way of heating a house. In order to meet this challenge, energy tariffs need to be set such that they encourage the consumer to make use of the right heating equipment. The authors calculated the total overall efficiency starting from the energy content of gas, down to the load for different heating methods.

The heating options considered were;

A. Heating using standard electric heater powered from a grid that is supplied from a gas power station,
B. Heating using a heat pump powered from the grid that is supplied from a gas power station,
C. Heating using a gas fed condensing boiler,
D. Heating using the heat from a combined heat and Power (CHP) while feeding the electricity it generates to the grid,
E. Heating using the heat from a CHP while feeding the electricity to increase the heat output using the electric heater,
F. Heating using the heat from a CHP while feeding the electricity to a heat pump to increase the heat output generated.

Figure 3 shows the above 6 permutations and the related consumer costs to generate 1 kWh of heat.

Method A of heating involves the lowest capital investment but has the highest cost for every kWh of heat. It has also the lowest efficiency and is therefore not a viable
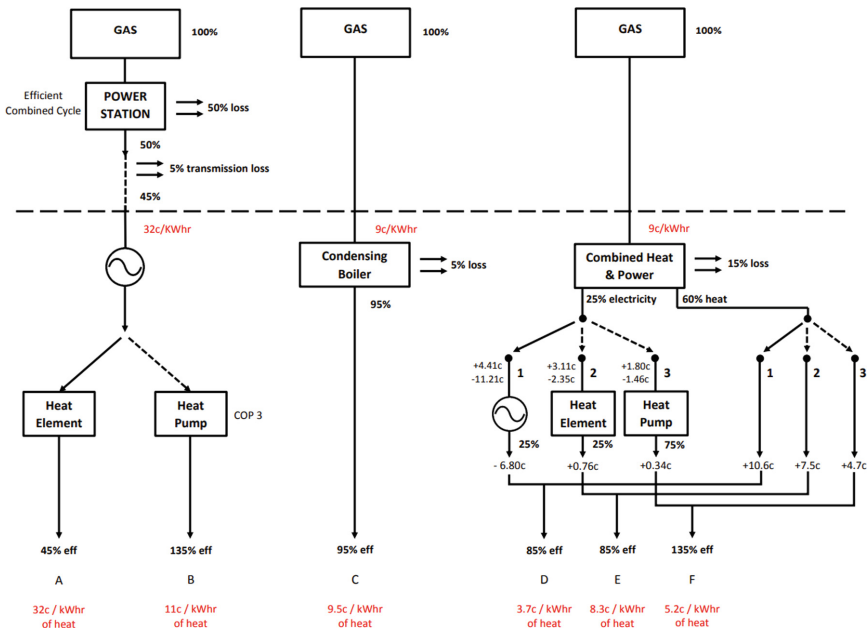

Fig. 3. Cost and efficiency of 6 possible ways of heating a house.

option. Method B involves the use of a heat pump and is a very efficient way of heating and is highly recommended. The cost per kWh is obviously much lower and depends on the coefficient of performance (COP) which was taken as three in this case. However, heat pumps with a higher COP are available today and it is definitely worth investing in the best heat pump with the highest COP. A heat pump has an important advantage in that one can also cool the house especially in extreme hot weather spells, which are now becoming more common during the summer months. Method C is also quite efficient when compared to A and is cheaper to run with the gas tariff used here. However, this can change, and energy providers should consider this change to encourage users to invest in heat pumps and operate at a much higher efficiency. This measure will definitely help in the reduction of gas consumption at source. Methods D, E and F involve a combined heat and power system, which, although requiring a substantial capital investment, offers a number of benefits which make it very attractive. The fact that you can generate electricity also means power is available during power cuts and you can also sell the extra electricity, which at present attracts an interesting feed in tariff. In fact, if this is done, as in method D, then this is the cheapest way of heating, for the tariffs considered, due to the feed in tariff return. However, this does not work out to be the most efficient way of heating unless others on the grid make use of this electrical energy to run a heat pump. Method E is also cheaper to run compared to methods A, B and C, however the efficiency is lower than that of B and C. Method F involves also the use of a heat pump and therefore is also very efficient and should also be recommended. Method F has the same overall efficiency as B but the running cost with these tariffs is less than half. This is because the heating is partly provided directly from the gas which results in a cheaper tariff than electricity. There is also the self-consumption return, which continues to decrease the overall cost of heating. With Method F one has the possibility to switch the heat pump to run directly from the electrical grid, as in Method A, especially for cooling. Although Method F is not the cheapest to run it definitely operates with the highest efficiency and can also be changed anytime to Method B which is also as efficient. Method F also has the advantage that in very cold climates the exhaust heat from the microCHP can be used to increase the efficiency of the heat pump or even allow it to operate at external ambient temperatures below 0 °C.

3 Cooking

Cooking is typically electric, gas or a combination of both. Electrical cooking usually demands high peak power especially if an electric or induction hob is used. Cooking does not require a lot of energy compared to the total energy requirement, as can be seen in Fig. 1, so the increase in the size and cost of the battery to support cooking in a house will not be so high. However, if one needs to power such appliances using energy stored in a battery, an inverter with high power rating will be required which involves a substantial investment. In the case that the grid is available, the authors recommend that electrical cooking equipment will be powered always from the grid. In case of grid failure, it would be useful to have a single LPG tank to supply a gas-powered hob. This tank can be also used to power up the microCHP. This method of cooking is quite popular in remote areas and in countries where gas grid is not available. LPG is usually also cheaper and one can expect 150kWh to 300kWh of energy in a single tank depending on the size.

4 Appliances

Today, we have a large number of appliances around the house. The most essential ones are the fridge and freezer usually positioned in the kitchen which is also close to a possible location of the micro hybrid CHP proposed in this paper. All the other appliances are usually spread all over the house and most of them are considered non-essential during a power cut.

PV ENERGY GENERATION IN A HOUSE

The renewable sources of energy widely used in houses are mainly two, photovoltaics and solar water heating. These are usually installed on our roofs preferably at that angle that yields the maximum yearly energy output. The authors compared the energy output of PV panels installed at 20° facing south to that from panels installed on a vertical wall facing south. This was done in both Malta and Germany (Fig. 4 and Fig. 6). As can be seen, in both cases, the yearly energy yield is much lower if the panels are mounted in a vertical position however the monthly yield in winter is better. If the panels are used for powering up the system shown in Fig. 2 then installing the panels used to a south facing wall (if available) is recommended since this tends to ensure that the grid is not required even in winter. One should also take into consideration that if snow falls, then the yield from panels mounted at an angle on the roof will go to zero. It is also useful to point out that installing PV panels to a vertical wall tends to be easier and cheaper.

Figures 5 and 7 show the output expected from a 1kWp PV system installed vertically for both cases. This is necessary at the system design stage, in order to estimate the number of panels required to ensure enough energy all year round.

Since less energy is required for lighting in summer, forced ventilation fans can be powered from the setup of Fig. 2 to keep the house cooler be switched on during night time, when both the and fresher in summer. The fans should preferably be switched on during the night when both the temperature and air pollution, are much lower.

ENERGY STORAGE POSSIBILITIES IN A HOUSE

For daily storage we can make use of various storages. We can store harvested energy in chemical storage (battery) or in heating/cooling of water, building material, and dwelling space.
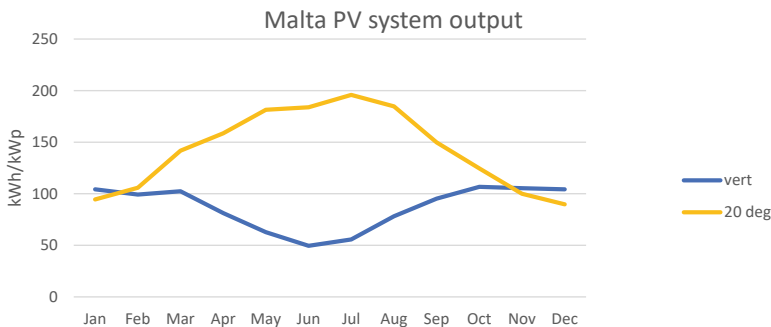

Fig. 4. Comparison of energy output between PV panels mounted vertical and at 20° facing south in Malta

In a household, energy can be stored in various materials or in batteries. The authors developed an interesting Table 1 to compare the energy that can be stored per kg weight and m^3 of volume for the materials and batteries that can be used. It is important to note that while the materials used are usually already available in a house, the batteries need additional space if they are to be used as storage. We have taken a typical temperature rise of the hot water to be 60 °C while we limited that of the building material to 20 °C.

HEATING AND COOLING SHORT TERM STORAGE

A substantial % of our energy demand is used for heating in winter and for cooling in summer. It is a fact that while daily storage of energy from renewable is possible, seasonal storage is not. There are different ways of heating but there is only one way of cooling, and this is using a heat pump.

For daily or short term storage, we can make use of various options. We can store harvested energy in chemical storage (battery) or by heating and/or cooling water, building material, and dwelling space.
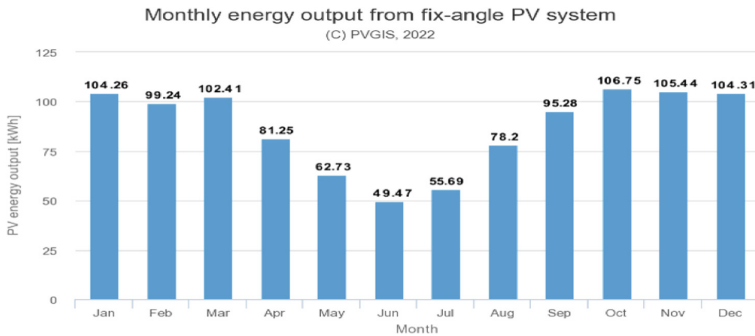

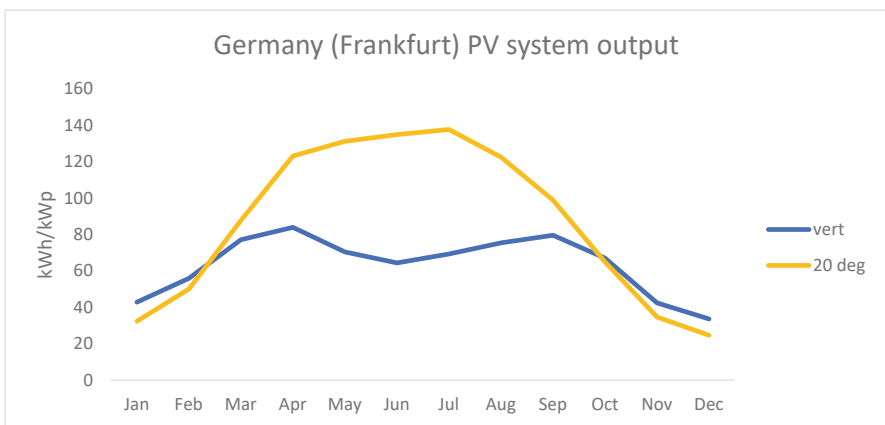**Fig. 5.** Monthly energy from vertically mounted south facing PV system (southern Europe)

Fig. 6. Comparison of energy output between PV panels mounted vertical and at 20° facing south in Frankfurt
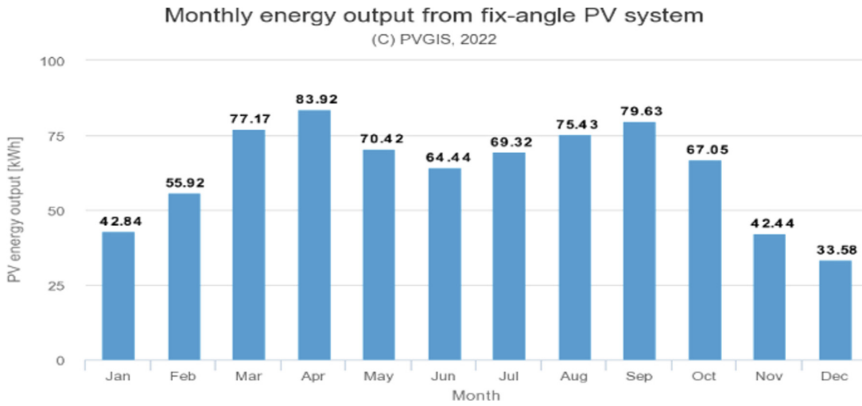
Fig. 7. Monthly energy from vertically mounted south facing PV system (Germany)

From Table 1, one can make a number of interesting observations. If we consider the volume as the principal parameter of interest, especially in a house, one can deduce that storing energy in water is comparable to storing energy in a lead acid battery. Therefore, storing energy from PV panels in a battery does not make much sense if it is then eventually used for heating. Recently a number of products [9, 10] emerged on the market that heat the hot water reservoir directly heated from PV panels. These products currently use standard heating elements making them cost effective. If one uses a heat pump water heater, one can multiply the efficiency by the COP at the expense of a higher initial cost.

Another interesting option is to store the heat in building material. The authors considered an apartment of 150msq with the height of the rooms being 2.9m. If we assume that we can raise the temperature of the building material by 20 °C then we can store;

1. 120 kWh in the internal dividing walls (180 mm thickness),
2. 350 kWh in the internal dividing side walls separating the property from 3rd Parties (230mm thickness),
3. 256 kWh in the front and back side of the building masonry (230 mm thickness),
4. 238 kWh in the floor slab (175 mm thick),
5. 2 kWh in the volume of air inside the apartment.

As can be seen a lot of energy can be stored in the building material. While storing energy in 2,3, and 4 is more expensive, as it involves high installation costs especially due to the insulation material required, option 1 offers the possibility of storing a substantial amount of energy with reasonable costs and relatively easy installation. As can be seen the amount of energy that can be stored in the air is negligible and this is also lost easily with the air changes in a residential house.

From this analysis, the authors concluded that the best way to store renewable energy is using a heat pump to vary the temperature of an insulated water reservoir in the house and then make use of any excess energy to circulate water through pipes in the dividing walls.

5   A DC MICROCHP DESIGN FOR HOME USE

An extensive technical research was carried out on previous work that made use of a single phase asynchronous machine in CHP applications [11–21]. In their first design, the authors [22, 23] concentrated on a microCHP with AC output that could be synchronized directly with the grid if required. This had a number of shortcomings and eventually this was changed to generate a DC output [3]. The DC output of our microCHP is now 48V, as it was evident that working with this voltage will reduce maintenance costs due to the fact that it is very safe to carry out the yearly service check without the need of qualified and trained personnel. The battery installed in the unit itself consists of 4, 12 V 25 Ah VRLA batteries. An external battery can also be connected directly to the DC input of the microCHP to increase the storage capacity.

The single piston engine is coupled directly to a three-phase delta-wound brushless generator and runs at around 4000 rpm. The three-phase output is then rectified and regulated to a DC voltage with the engine speed controlled to ensure the correct voltage for an IU charging characteristic when the battery is being charged. Most of the 2 kW electric power output goes to the external inverter. The brushless machine being directly coupled to the engine made it possible to easily use it to start the ICE, eliminating the need of a starter motor. This design also eliminated the need of a separate 12 V starter battery since the machine can be started directly from the embedded battery storage.

Fig. 8. Impression of the microCHP installation
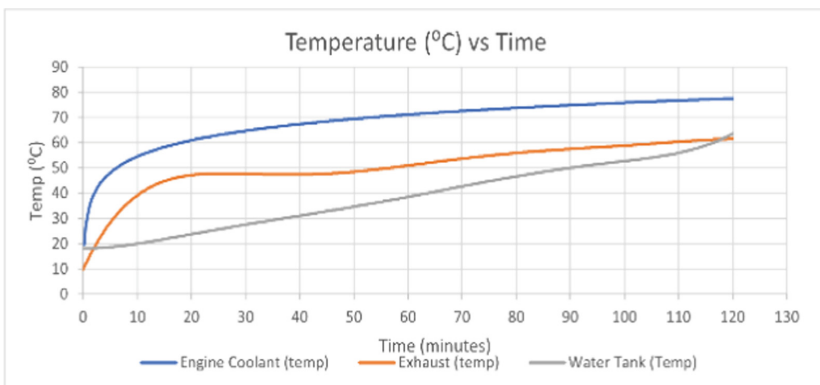

Fig. 9. Temperature performance of microCHP coupled to a 200 ltr water tank and supplying an electrical load of 2 kW

The size of the microCHP with the integrated battery is equivalent to that of a standard kitchen appliance and its housing was designed to ensure that it could be easily fitted in the kitchen cupboard even of a small apartment Fig. 8 shows an artistic impression of how the microCHP can be integrated in a kitchen cupboard. The output exhaust temperature from the microCHP which runs at an efficiency of 85% can only reach a maximum temperature of 70 °C and therefore the exhaust gas can be channelled to the outside using plastic pipes.

The authors have put a lot of effort to ensure maximum heat recovery within the limited space. The device was connected electrically to a constant resistive load and the water circuit was connected to a 200 L water tank. The results, shown in Fig. 9, were very promising as the secondary water circuit was maintained at a comfortable operating temperature throughout the tests. The exhaust temperature at the engine manifold of 800 °C was dropped by the exhaust heat exchange circuit to an approximate value of 40 °C when the temperature of the tank water was 20 °C. This increased to a maximum of 70 °C when the water temperature reached 60 °C after 2 h continuous operation under full electric load of 2 kW.The thermal design includes 2 thermal air flow circulating circuits as shown in Fig. 10. The microCHP housing was internally split into 2 partitions to also recover the thermal energy emitted from the battery, control electronics, and electrical generator which is considered to be equivalent to around 5% of the total heat energy generated.

This could be possible since the size of the microCHP was reduced to that of a domestic appliance and therefore it can be placed in the apartment/house rather than in a garage or basement. Figure 11 shows a photo of the first samples of the microCHP that are currently being tested in a number of households.

This heat recovered battery and generator compartment can easily heat the room where the microCHP is installed while it is running. The generator integral cooling fan

Table 1. Energy storage capacity per weight and volume of different materials and batteries

| Heat/energy Capacity	Density	Material/battery	Storage weight (Wh/kg)	Storage space (Wh/m³)
4190 J/kgK	1000 kg/m³	Water with 60 °C temp rise	69.80	69,833
1000 J/kgK	2000 kg/m³	Stone with 20 °C temp rise	5.6	11,120
800 J/kgK	1800 kg/m³	brick with 20 °C temp rise	4.5	8,006
1000 J/kgK	2200 kg/m³	Concrete with 20 °C temp rise	5.6	12,232
1000 J/kgK	1.2 kg/m³	Air with 20 °C temp rise	5.6	7
40 Wh/kg	80 Wh/ltr	lead acid	40.0	70,064
150 Wh/kg	160 Wh/ltr	lithium	200.0	150,120
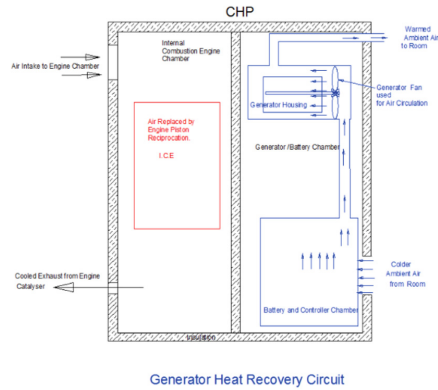
Fig. 10. microCHP with integrated storage

Fig. 11. Photo of microCHP Engine and battery housing

is used to draw air from the room. The air first flows over the battery compartment, then onto the control electronics, then over the generator and finally the warmer air flows back into the room. Another air flow circuit is formed by the inlet and exhaust of the ICE engine. The air is drawn into the engine inlet manifold from an outside source (e.g. a shaft). The engine compresses the air and after the combustion cycle it is exhausted outside (can be the same shaft). The exhaust system has an embedded catalyser and reaches Euro6 standard.

A PRACTICAL IMPLEMENTATION OF A SMART HOME SYSTEM USING PV'S, CHP AND A HEAT PUMP

The authors were involved in the renovation of a typical small townhouse in Malta and in view of the above research decided to opt for the setup of Fig. 12. The two storey, old house of character has double walls all round providing reasonable insulation. Since these walls cannot be altered as they are protected by heritage laws, underfloor water heating was chosen as a heating method. The Ground floor underfloor piping covers 57 sqm which includes the Kitchen, Guest Bathroom & Dining Room. The first-floor underfloor piping covers 46 sqm and runs through the Main Bedroom & Ensuite

bathroom. The DC microCHP shall assist in the heating in winter and provides the lighting and communication circuit power through its battery all year round. In summer the microCHP battery is charged from the PV panels.

The house is currently grid connected and also has a 3 kWp PV installation on the roof. The PVs are used for self-consumption mainly, however the energy that is not consumed is exported to the grid. In Figs. 13 and 14, the blue column represents energy imported from the grid, the yellow colour shows solar energy that was self-consumed while the purple colour represents the solar energy that was exported to the grid.

The thermal energy (underfloor heating/cooling and domestic hot water) is supplied from a heat pump. The system has been running since December 2021, Fig. 13 and Fig. 14 show two samples of energy flow taken in winter and in summer. It is very clear that with such a setup the house is generating more than 100% of its energy requirement in summer, and more than 50% of its energy requirements in winter.
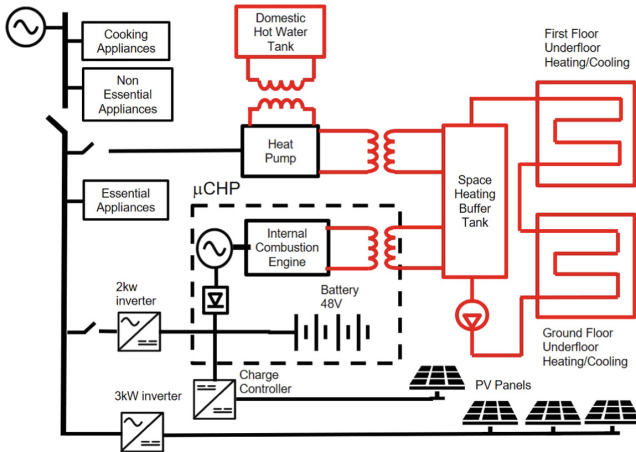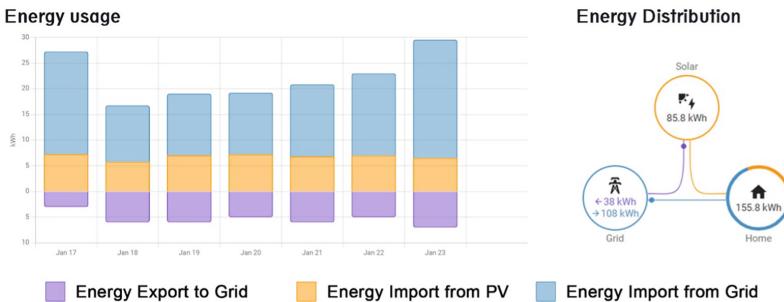

Fig. 12. Block diagram of smart setup
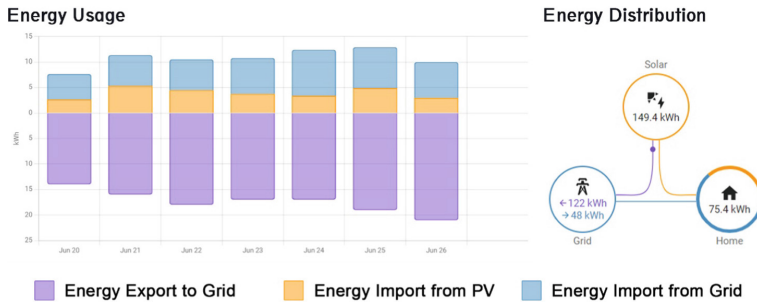

Fig. 13. Winter energy use

Fig. 14. Summer energy use

The authors plan to introduce the microCHP during next winter season, this is expected to reduce the electrical energy import (blue column) during the winter season and thus shift the house towards generating the 100% energy requirement during winter. Further results of this setup will be published in future work.

CONCLUSION

In this paper the authors have provided an overview of the various possibilities of generating and storing energy in a house. It is important that each design should start with an energy audit of existing buildings, whilst for new building developments it is important to start collaborating with an architect at an early design stage. The paper clearly shows that while a heat pump provides a substantial impact on the consumption of the gas used, PVs and a microCHP with an integrated battery will help in providing a substantial amount of the yearly energy needs. The use of the microCHP, which has been developed and patented, will also enable the owner to become grid independent if required.

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