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Optimal micro-CHP configuration for the NPA Region

Micro Combined Heat and Power System for Households
Deliverable D.T1.4.1

H-CHP

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Overview

The purpose of this report is to describe the various possibilities for using Combined Heat and power (CHP) in homes within the NPA region and to list the various funding schemes available in the appropriate countries.

The report gives an overview of current technologies available for micro CHP systems and outlines a specification for a new product that will best meet the market needs.

Included is a model of a hybrid system incorporating solar PV panels operating with the micro-CHP system and an analysis is made to determine if the additional cost outweighs the advantages. An entirely off-grid system is considered since this would be of significant advantage in the area.

There is also a recommendation on whether the electricity produced should be stored for internal use or exported to the grid.

This activity will draw together the information from DT 1.1 - DT1.3 and proposes a manufacturing cost range, size range, acceptable noise levels, and electricity to heat ratio performance. The analysis will consider the cost differences between prototype construction, low volume production and high-volume manufacture. This ensures the product will best meet market needs in the NPA region that can be widely adopted as the product of choice at the end of the project.

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Executive Summary

Overall benefits summary for using a micro CHP system

- Reduction in Operational Costs
- Reduction in CO_2 emissions
- Stable heat energy supply
- Additional benefits due to electricity generation
- Possibility of using alternative burners for solid fuels
- Possibility of upgrading existing system
- Possibility of combining the micro CHP with Solar PV system and battery storage for Off-Grid operation

Due to a harsh environment, low ambient temperatures, high humidity level and other extreme weather variations, NPA countries' households should consider adopting an appropriately designed CHP system. In contrast with southern countries where households consume more electrical energy than heat for their needs, NPA area households are using about 85% of the energy for water and space heating. Therefore, the electricity-to-heat ratio for a micro CHP system should be between 1/6-1/7.

Background research on available micro-CHP technologies helped to identify the advantages and disadvantages of different systems. The summarised comparison table is provided in the report. It was identified that optimal technology for the micro-CHP system for NPA area was a Stirling Engine. The Stirling engine has advantages such as electricity-to-heat ratio, low noise level, large maintenance intervals and can be used with any types of fuel as well as being able to be integrated into existing heating systems.

Other technologies such as gas micro turbines or steam engines have severe limitations such as risk of explosion, high noise level and low maintenance intervals due to the corrosive nature of the steam. These make them unsuitable for the application.

EU countries' governments support installation of renewable energy technologies. As an example, the UK's Renewable Heat Incentives would be able to cover the biomass fuel costs, while electrical energy generation from renewable sources could bring additional financial benefits through the Feed-in-Tariff scheme, excess energy export to the grid and savings due to electricity import reduction.

The feasibility of three different electrical grid connection models were assessed:

1. Grid-tied micro CHP system
2. Battery-assisted grid-tied micro CHP system
3. Combined micro CHP and Solar PV system with electrical energy storage

In first scenario, 19,566kWh of thermal energy and 1183.8kWh of electrical energy would be generated by the CHP system over the period of one year. The primary output of the system is thermal energy and electrical energy is the secondary output (heat-to-electricity ratio 9/1).

As there will be periods when electrical output of the system will exceed the household demand, some energy might be exported to the grid. According to the simulation model, the exported energy is estimated to be approximately 419.6kWh a year.

For a grid-tied micro CHP system to cover the household electrical energy deficit when the CHP is not operating and is not generating enough power the electrical energy import will be 3125.7kWh (80.4% of the total demand).

As a second scenario, a battery-assisted grid-tied system was proposed. The main benefit of this system is that a low-value electrical energy generated during the CHP system "ON" periods, can be stored and used later when demand is high, thus providing additional benefits on electrical energy savings and reducing the number of hours of the electrical energy import. Integration of the electrical energy storage into the system could also provide faster response to household demands.

The integration of the solar photovoltaic system with a total installed capacity of 4.16 kWp and higher capacity electrical energy storage system was investigated in the third scenario. The solar PV system was estimated to be able to supply extra 3291.5kWh of energy per year. According to the simulation model, the micro CHP system with electrical power output of 1,400 Watts would be able to cover in full the electrical energy requirements for a single household. The optimal electricity-to-heat ratio is 1:6.

The financial projections were prepared for all three scenarios. System specifications, energy output, fuel prices, fuel input and other variables were considered in the calculations.

The payback time for the grid-tied micro-CHP system is estimated to be 8.65 years and the ROI (Return-on-Investment) rate will be approximately 11.56%. The financial benefits of the micro CHP system will overtake the oil-fired heating system after approximately four years of operation. Installation of a high capacity electrical energy storage and solar photovoltaic system will increase the initial cost of the system by 45% from £20,000 to £29,000. However, the payback time of the system is estimated to be 7.3 years and is the shortest comparing all scenarios. The ROI rate for this scenario will be approximately 13.67%.

The main environmental impact of heating systems is the emission of CO_2. A Combined heat and power system is an alternative that may have a lower environmental impact, especially when burning biomass fuels.

According to the data from simulation, the proposed biomass micro-CHP system will offset as much as 96.55% of greenhouse emissions compared to the existing oil-fired boiler. Having the average efficiency of 60% the oil-fired boiler annual fuel input was identified to be 3261 Litres. When burning this amount of fuel, about 8041.3 kg CO_2 are emitted into the atmosphere. Whereas, the total CO_2 emissions for the biomass micro-CHP system will be 277 kgCO_2.

1. Introduction

A Combined Heat and Power (CHP) device uses the principle of co-generation – simultaneous generation of electricity and heat – resulting in more efficient extraction of the energy from the fuel.

All thermodynamics conversions result in some energy loss during the heat-to-electricity transformation process (Shavit, 1995). This waste heat can be captured and used for other needs, increasing the overall efficiency of the cycle.

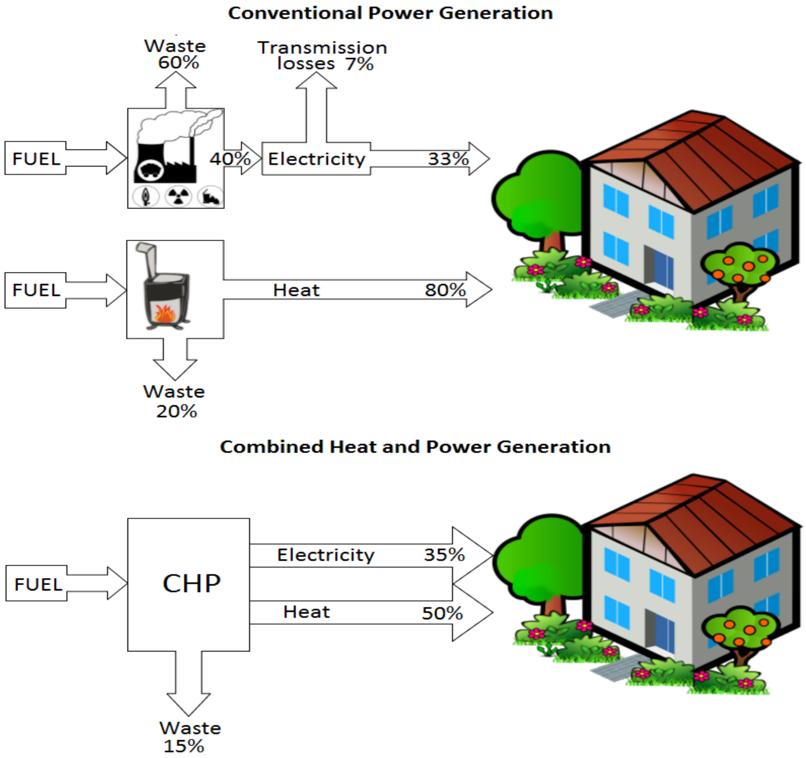

Figure 1 CHP Efficiency

The well-known applications of the CHP are Combined Heat and Power District Heating (CHPDH). This is a popular solution in northern countries, when waste heat from power plants is used for heating the buildings in nearby areas.

More relevant for this study is Local CHP and Distributed Generation that can be used to produce the power for individual projects. This model can be for either industrial applications (when heat is used for heating the premises and electricity for manufacturing processes), or domestic applications (Micro-CHP). Excess power from individual CHP units can be stored or exported to the grid.

2. Government Projects, Incentive Schemes and Funding

The European Union policies and routemaps for renewable energy generation define the needs of increasing the number of combined heat and power generation units. Cogen, Europe the European Association for the promotion of cogeneration *"works at the EU level and with member states to develop sustainable energy policies and* *remove unnecessary barriers to implementation"* (Cogen Europe). The feasibility study prepared for Cogen Europe determines five key benefits of distributed micro-CHP generation for the EU, it:

- provides energy for consumers.
- balances generation from renewable sources, providing more stable supply than intermittent wind turbines or solar PV generators.
- significantly reduces carbon dioxide pollutions during heat and electricity production by more efficient use of fuels.
- provides energy security.
- supports Europe's economy, creating new jobs and adding value to the EU economy.

A range of projects is supported by the EU government to help the widespread the development of the CHP technologies.

3. The UK Renewable Incentive Schemes

The UK government supports the installation of new micro-CHP systems by developing incentive schemes for electricity generating technologies (Feed-In-Tariff, FIT), and heat generating technologies (Renewable Heat Incentives, RHI). The full list of technologies eligible for FIT and RHI from Microgeneration Certification Scheme (MCS) can be found in BS EN ISO/IEC 17065:2012 document.

The Office of Gas and Electricity Markets (OFGEM) describes the **Feed-In-Tariff** as a government programme designed to promote the uptake of small-scale renewable and low-carbon electricity generation technologies. It means that if you have an eligible installation, you could be paid for the electricity you generate as well as for the surplus electricity you export to the grid. (FIT+Expot rate). *To be eligible for FIT Micro-CHP should not exceed 2kW electrical power output.*

The Domestic Renewable Heat Incentive (**Domestic RHI**) is a government financial incentive to promote the use of renewable heat. Switching to heating systems that use eligible energy sources can help the UK reduce its carbon emissions and meet its renewable energy targets. (OFGEM). Members of the RHI scheme are paid quarterly for seven years the amount of renewable heat produced by their systems.

Funding Opportunities:

- HEEPS Loan Scheme
- HEEPS 25% Cashback Scheme
- Warmer Homes Scheme
- Cold Weather and Winter Fuel Payments
- Warm Home Discount

4. The EU Renewable Incentive Schemes

Information was gathered from the RES LEGAL Europe website which provides details on the regulations of the renewable energy generation, the important legislation on the renewable energy support schemes, analysis of the grid issues and policies for energy from renewable sources covering all three energy sectors: electricity, heating & cooling and transport. The scope of the RES LEGAL database covers all the EU 28 Member States, the EFTA Countries and the Members of the Energy Community. This report provides summary information for the Northern Periphery and Arctic Programme member countries:

Norway	Sweden	Finland
Greenland	Iceland	Republic of Ireland
Northern Ireland	Scotland	Faroe Islands

The information available on the RES LEGAL website contains a links to all relevant original legislation, is free of charge and is regularly updated.

4.1 Norway

Summary

Norway promotes renewable energy through a quota system including a certificate trading scheme.

Electricity Support Schemes

The main incentive for the use of renewable energy is a quota system in terms of quota obligations and a certificate trading system. The Electricity Certificates Act obliges electricity suppliers and certain electricity consumers to prove that a certain quota of the electricity supplied by them was generated from renewable sources. Such proof shall be provided by means of tradable certificates allocated to renewable energy producers.

Sweden and Norway introduced a common electricity certificate market on 1 January 2012.

Further Information

Olje- og energidepartementet (OED) – Ministry of Petroleum and Energy - + 47 22 24 90 90

OED website: postmottak@oed.dep.no

Norges vassdrags- og energidirektorat (NVE) – Norwegian Water Resource and Energy Directorate

+ 47 22 95 95 95 - NVE website: nve@nve.no

Statnett – Norwegian transmission system operator - +47 2390 3000

Statsnett website: firmapost@statnett.no

4.2 Sweden

Summary

Sweden promotes renewable electricity through a quota system, tax regulation mechanisms and a subsidy scheme. In Sweden, tax exemptions are the main incentives to support renewable heating. The main incentive for renewable energy use in transport is a tax exemption for biofuels.

Electricity Support Schemes

Quota system. The main incentive for the use of renewable energy sources is a quota system with quota obligations and a certificate trading system. The Electricity Certificates Act obliges energy suppliers to prove that a certain quota of the electricity supplied by them was generated from renewable energy sources. Energy suppliers must provide this evidence by presenting tradable certificates allocated to the producers of electricity from renewable sources.

Tax regulation mechanisms. Electricity generated from wind energy is eligible for tax privileges consisting in a reduction of the real estate tax as defined in the Act on the Federal Real Estate Tax. Electricity produced in electricity generators with a capacity lower than 50 kW is not taxable. For electricity generated from wind, wave and solar this capacity margin is higher as authorised by the Energy Tax Act. Since 2015, a tax reduction for the micro production of renewable electricity is in place.

Subsidy. Sweden grants subsidies for photovoltaic installations.

Heating&Cooling Support Schemes

Tax reductions for households. Act No. 2009:194 sets rules for the tax-deduction of RES-related installation works in households. The installation of renewable energy devices and the replacement of conventional heating sources with renewable ones may be deducted from tax.

Energy and carbon dioxide taxes. In Sweden, energy and carbon dioxide taxes are levied on the supply, import and production of fossil fuels for heating purposes. Renewable energy sources are exempt from these taxes.

Nitrous oxide tax. The producers of heat are obliged to pay a tax according to their nitrous oxide emissions. Heat producers using renewable energy sources are exempt from this obligation.

Further Information

Energiemyndigheten – Swedish Energy Agency -+46 165 442 000

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Boverket – Swedish National Board of Housing, Building and Planning - +46 455 353 000

registraturen@boverket.se

Naturvårdsverket – Swedish Environmental Protection Agency - +46 10 698 10 00

Naturvårdsverket website: registrator@swedishepa.se

Skatteverket – Swedish Tax Authority -+46 771 567 567

Svensk Fjärrvärme – Swedish District Heating Association - +46 8 677 25 50

kontakt@svenskfjarrvarm.se

4.3 Finland

Summary

In Finland, electricity from renewable energy sources is mainly promoted through a premium tariff. The tariff applies to electricity produced from wind, biomass and biogas. Additionally, investments in RES are supported through state subsidies. The main support mechanism for heat produced from RES is a “heat bonus” allocated to CHP plants working on biogas and wood fuel.

Electricity Support Schemes

Subsidies. The state of Finland provides subsidies for investment and research projects in the field of sustainable energy generation.

Premium tariff. The producers of electricity from wind, biomass and biogas sell their electricity in the market and receive a variable bonus, which is paid on top of the market price and is equal to the difference between a target price and the market price.

Heating&Cooling Support Schemes

Heat production from renewable energies is subsidised through various support schemes and investment aids.

Heat Bonus. A fixed “Heat bonus” is paid for heat produced by CHP plants working on biogas and wood fuel.

State grant for investment in RES. Investment supports are available for the construction of production facilities using renewable energies.

Investment support for farmers. Investment support is available for farmers to support the construction of heat plants working on renewable energy.

Further Information

Työ- ja elinkeinoministeriö (TEM) – Ministry of Economic Affairs and Employment - +358 295 16001

kirjaamo@tem.fi

Maa- ja metsätalousministeriö – Ministry of Agriculture and Forestry - +358 (0) 295 16 001

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Elinkeino-, liikenne- ja Ympäristökeskus – Centre for Economic Development, Transport and the Environment

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4.4 Denmark

Summary

In Denmark, electricity from renewable sources is mainly promoted through a premium tariff and net-metering. The premium tariff for offshore wind farms is awarded through tenders. Renewable energy sources for heating are exempt from the tax obligations on the production, supply and use of energy sources. The use of biogas for heating purposes is supported through a direct tariff.

Electricity Support Schemes

Premium tariff. Generation of electricity from renewable sources is promoted through a premium tariff system based on bonus payments. The operators of renewable energy plants usually receive a variable bonus, which is paid on top of the market price. The sum of the market price and the bonus shall not exceed a statutory maximum per kWh, which depends on the source of energy used and the date of connection.

Tenders. Premium tariff for offshore wind farms is awarded through tenders.

Net–Metering. Electricity producers using all or part of the electricity produced for their own needs are totally or partly exempt from paying Public Service Obligation on this electricity. The Public Service Obligation is a charge levied to support renewable energy.

Loan guarantees. Associations of wind energy plant owners and other local initiatives may apply for guarantees for loans for feasibility studies that are conducted in the run-up to the construction of a wind-energy plant.

Heating&Cooling Support Schemes

Tax regulation mechanism. In Denmark, there are different taxes on the production, processing, possession, receipt and dispatch of fossil fuels for heating. Renewable energy sources are exempt from these taxes.

Price based mechanism. The use of biogas for heating purposes is supported through a direct premium tariff.

Further Information

Energistyrelsen (ENS) – Danish Energy Agency - +45 339 267 00 ens@ens.dk

Skatteministeriet (SKM) – Danish Ministry of Taxation - +45 33 92 33 92 skm@skm.dk

Danish District Heating Association - +45 76 30 80 00 mail@danskfjernvarme.dk

Energi-, Forsynings- og Klimaministeriet (EFKM) – Danish Ministry of Energy, Utilities and Climate - +45 339 228 00 efkm@efkm.dk

4.5 Iceland

Summary

In Iceland, the generation of electricity from renewable energy sources is promoted by subsidies granted for the design and construction of original tools and equipment for research on and the exploitation of energy resources as well as for special projects in the field of economical energy use.

Access of renewable energy plants to the grid is subject to the general legislation on energy. As all electrical energy consumed in Iceland is generated from renewables, RES are not given priority grid connection.

Support Schemes

Subsidy: National Energy Fund

Grants are offered for exploiting energy resources and for special projects in reducing energy use.

Further Information
Atvinnuvega- og nýsköpunarráðuneytið – Ministry of Industries and Innovation - +354 545 9700
Ministry of Industry, Energy and Tourism website - postur@anr.is
Orkustofnun – National Energy Authority - +354 569 6083
Landsnet – Transmission system operator -+354 563 9300

4.6 Republic of Ireland

Summary

In Ireland, electricity from renewable sources was mainly promoted through a feed-in-tariff scheme (REFIT) until 31 December 2015. Currently there is no support scheme available for producing electricity from renewables but a new support scheme was been announced in March 2017. Renewable energy sources for heating purposes are promoted through a grant and a tax return.

Heating&Cooling Support Schemes

Subsidy I: The Better Energy Homes scheme allows homeowners of dwellings built before 2006 to apply for a €1,200 grant aid for installing solar heating.

Subsidy II: Better Energy Warmer Homes scheme delivers a range of free energy efficiency measures to low-income private households who are vulnerable to energy poverty. To be eligible applicants must receive of one of the following:

- Fuel Allowance as part of the National Fuel Scheme;
- Job seekers allowance for more than six months and with children under 7;
- Family Income Support.
- One-Parent Family Payment

Tax regulation mechanism: The Accelerated Capital Allowance (ACA) scheme encourages investments in energy efficient equipment and allows companies to depreciate 100% of the purchase value of qualifying energy efficient equipment against their profit in the year of purchase.

Further Information

Department of Communications, Energy and Natural Resources (DCENR) - +353 167 82 000

Sustainable Energy Authority of Ireland (SEAI) - +353 1 808 21 00, info@seai.ie

Revenue Commissioners (Revenue): Irish Tax and Customs - +353 1 702 3011

5. Design and Implementation

5.1 Demand Analysis

According to the energy consumption information from the survey, the system requirements are:

- Electrical energy – 330 kWh per month/11kWh per day
- Thermal energy - 14258 kWh per year/approximately 1200kWh per month

To assess the efficiency of the system for a specific location, a simulation model was produced.

The weather information included in the model was hourly average outdoor temperature, relative humidity and wind speed was acquired from the local Wind farm (Figure 2) covers a period from 23 March 2010 to 23 March 2011.

Figure 2 site position on Google maps

Information on solar irradiation was taken from the European Commission Joint Research Centre (JRC), Photovoltaic Geographical Information System (PVGIS). The information shows the Global irradiance on a fixed plane (W/m^2) at the optimum inclination angle for the specific location (42 degrees for Stornoway). The information on solar irradiation for any other locations can be easily extracted from the PVGIS database and incorporated into the simulation model for more accurate results.

To define the specific heat demand two input variables are needed:

$$Q = U * A * dT \qquad \text{(Eq. 1)}$$

Where dT - temperature differential obtained between the indoor comfort temperature (set point) and hourly average outdoor temperature, and U-value or energy performance of the building. The average energy performance of the building in W/K for specific location was obtained from the energy consumption survey (Deliverable T1.1).

To check whether the heat loss calculations are right, two other concepts were employed. The information from the “Energy Consumption in the UK 2017” (BEIS, 2017) report published by the Department for Business, Energy and Industrial Strategy confirms that in average of 13,801 kWh of energy per year are used by each household for heating purposes, and 3,889 kWh of energy are used to cover the electricity demand.

Also, Heating Degree Days concept was used for calculating the annual energy requirements and building heat losses recommended by the Chartered Institution of Building Services Engineers (CIBSE) and shows similar results:

Annual heat loss = Building Heat Load*HDD*24hours (CIBSE, 2007)

	Threshold temperature	Annual Heat Loss
CIBSE data (Stornoway, 2671 HDD)	15.5^{0}C	11538.72 kWh
Excel simulation	15.5^{0}C	11159.23 kWh

Table 1 Annual Heat Loss

Naturally, the annual heat loss will be higher if threshold temperature is set higher.

5.2 Electrical Demand Modelling

To model the electricity demand, the data from the Department for Business, Energy & Industrial Strategy (BEIS) and data from the Digest of UK Energy Statistics (DUKES) was integrated into the synthesised electrical demand profile model from the D.P. Jenkins, S. Patidar and S.A. Simpson. This model shows the demand profile for a single dwelling and considers the electrical energy consumption peaks in contrast to aggregated profile data where peaks are smoothed.

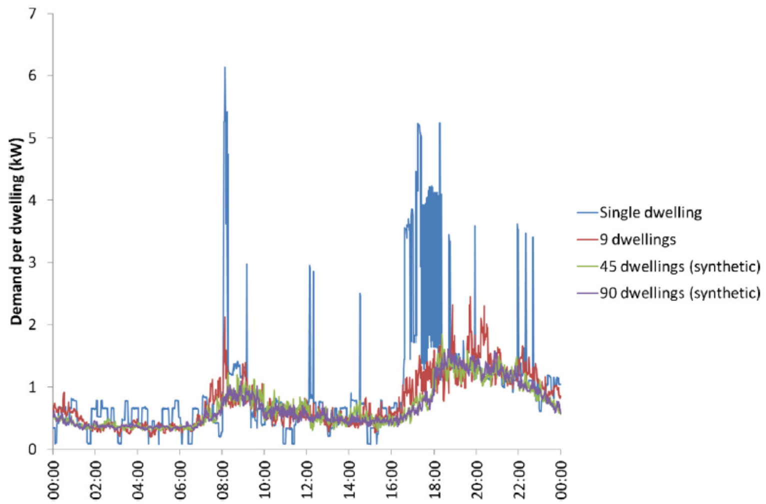

Figure 3 Comparison of diversity in profiles for single and multi-dwelling datasets. (Jenkins, Patidar and Simpson, 2014)

5.3 System Description

Comparison of the micro CHP technologies (Table 8 Comparison of micro CHP Technologies., page 36) shows that the Stirling Engine generator has some advantages:

- Low noise level (compare to Internal Combustion Engines and Gas Turbines)
- No internal combustion
- No risk of explosion due to high-pressure steam operation
- Any fuel type can be used
- Can be connected to any existing heating system
- Large maintenance intervals

It was decided to design a micro CHP with a Stirling Engine generator to fulfil the customer requirements. To be eligible for the Microgeneration Certification Scheme incentive, the power of a Stirling Engine generator should not exceed 2kW (MCS, 2017). Also, the solar PV modules can add an extra capacity to the electrical system.

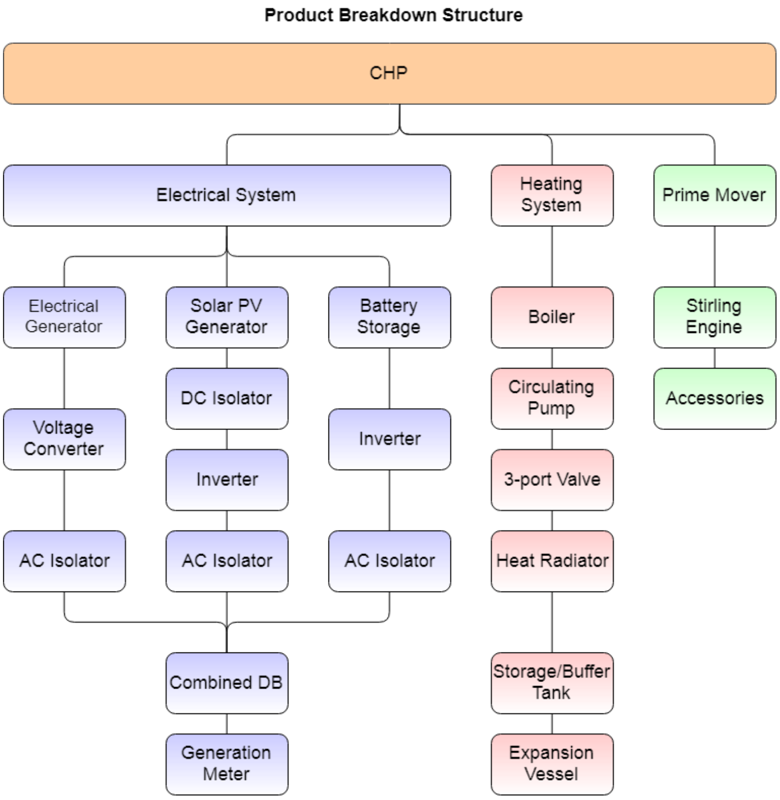

Figure 4 Product Breakdown Structure.

The CHP system can be subdivided into three subsystems:

1. Heating System

The Heating system consists of a boiler, thermal storage tank, circulating pumps, valves and expansion vessels. If the heating system is installed already and operational, then only flexible connections are needed to connect the Stirling Engine to the hot water flow and cooling water supply.

2. Prime Mover

Stirling Engine.

3. Electrical System

The **generator** converts the mechanical power from the prime mover into electric power. Generators for specific applications are available from various manufacturers in the UK and Europe. Prices range from £300, depending on output required.

Solar PV Generator – converts energy from the sun into electrical energy. In this case a LG NeON® 2 Black model LG320N1K-A5 320W 13 monocrystalline solar PV modules with Total Installed Capacity of **4.16 kWp** was chosen.

Electrical Energy Storage – variable **3.5kWh** lead-acid battery storage system for grid supported CHP system, and Tesla Powerwall® 2 **13.5kWh** storage system with integrated power inverter for the Off-Grid system were selected.

Accessories – Power Inverter, Generation meter, SMA Smart Meter, Home Energy Manager, cables, circuit breakers, isolators, distribution boards.

Technical Specifications

Micro Combined Heat and Power System Specifications 01/07/2018 Revision A.	
1. Performance	
Net Electric Power	0.6 kW
Net Thermal Power	9 kW
Electricity to heat ratio at max power	1/15
Total Efficiency	95 %
Grid connection	230V / 50 Hz
2. Fuel	
Wood pellets ISO 17225–2, class A1	
3. Heating system	
Water flow Temperature	+5+85 °C
Water return temperature	+5+60 °C
Water buffer tank temperature	+5+85 °C
Max. permissible operating pressure	3 bar
4. Installation and maintenance	
Installation	By skilled personnel only
Service intervals	1 per year

Table 2 Technical Specifications of the micro CHP.

5.4 Simulation Model Description

The simulation model allowed the energy requirements to be calculated and fuel input based on a household heat and electricity demands, weather data and system specifications. Each system component can be varied, and weather information can be actuated according to a specific geographical location. Furthermore, the use of this system model evaluates each component sizing and the impact it had on the system through a year time span.

Process

The outdoor temperature, building heat losses and thus heat energy demand, are primary factors for the control of the CHP system.

Other system inputs are:

CHP	Thermal Energy Storage	Solar PV System
Heat output Electrical output ON/Off temperature System efficiency	Tank capacity Working fluid density Heating system losses	Hourly average solar irradiation Solar PV System Total Installed Capacity

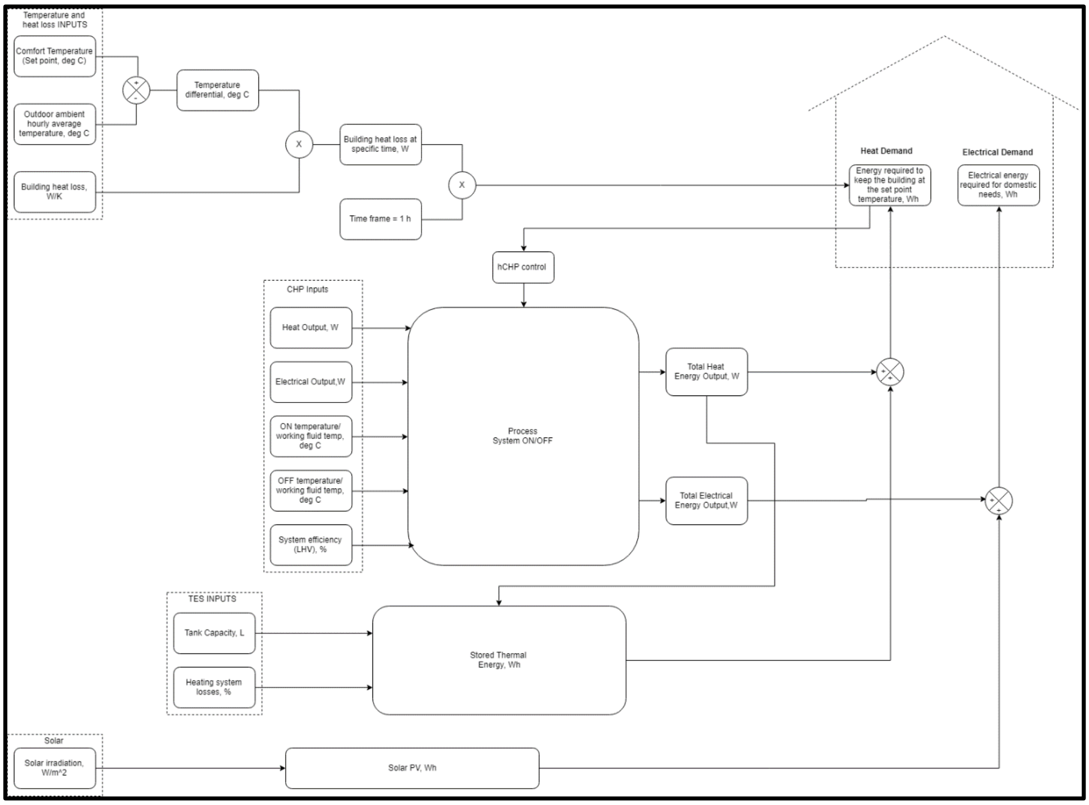

Figure 5 H-CHP simulation model diagram

ON/OFF logic

The CHP system will switch ON when the temperature in the thermal energy buffer tank drops below 42^{0}C and will stay ON unless it reaches the maximum storage temperature of 85^{0}C. The system will switch OFF when temperature in the thermal energy storage buffer tank rises above 85^{0}C.

Thermal and electrical energy generation and output

CHP System Specifications		
Thermal Output 1st hour	4.5	kW
Thermal Output Nominal	9	kW
Electrical Output Nominal	0.6	kW
Off Temperature	85	C
On Temperature	42	C
Efficiency (LHV)	0.95	

Table 3 CHP System Specifications.

According to the system specifications the nominal power output of the CHP system is 9kW thermal and 0.6kW electrical. The H-CHP will incorporate a Microgen® Free Piston Stirling engine for generating electricity. This will generate electricity, (230 V, 50 Hz) which will be available for the use in the house or for feeding into the public power grid.

The nominal electrical power output is 600 Watts, whereas the maximum power can reach the outputs of up to 1050 Watts. For the excel model, it was assumed that electrical energy will NOT be generated by the CHP system over the first hour of operation after the starting-up.

We will also assume that during the first hour of operation after the starting-up the system will produce only 4500Wh of thermal energy as it needs to reach the nominal parameters.

Thermal energy storage

The thermal energy will be supplied to the radiators (house heating system) to cover the heat needs of the house first. Any surplus energy will be stored in the TES buffer tank. As the temperature in the buffer tank reaches 85^{0}C, the boiler switches OFF and energy for the house heating system will be supplied from the buffer tank.

Thermal Energy Storage		
Capacity	605	L
Mass of water	608.63	kg
Heat Losses	0.1	
Water density	1006	kg/m^3
Water specific heat capacity	4.17	kJ/kgK

Table 4 Thermal energy storage specifications.

Energy Storage characteristics and maximum storage capacity

The Excel model shows energy content, temperature and considers the losses associated with the energy storage and transmission.

The feasibility of three different electrical grid connection models were assessed. These were:

Grid-tied. Where surplus electrical energy generated by the CHP system can be exported into the electrical grid or imported from the grid when required.

Battery assisted grid-tied. Where the surplus electrical energy generated by the CHP system is fed to the electrical storage battery first, and then partially exported into the electrical grid. It can also be imported from the grid when demand is high.

Solar PV+battery+grid/off-grid. Where extra information on solar irradiation for the specific geographical location can be included. A supplementary solar PV system should cover the electrical energy deficit.

Grid-tied

R column – "Export/Import" shows the difference between generated electricity and household demand. Negative values correspond to deficit and shows the amount of energy imported from the grid. Positive values show the amount of energy exported into the grid.

	A	B	C	D	E	I	J	K	L	M	N	O	P	Q	R
1			set point temp	Heat loss (W)	Electrical demand (Model)	Energy Generated by CHP			CHP Inputs			Thermal Energy Storage			Electricity t
2	Date	Temp	20	180	kWh	Heat, Wh	Electrical, Wh	On/Off	Fuel Input,W	Fuel Price	Heat-Demand	Energy In/Out Wh	Buffer,kJ	Temp, C	Export/Import, kWh
3	27/03/2010 10:00	1.709	18.291	3292.38	0.502	0	0	0	0.00	0	-3292.38	-3292.38	731320.98	15.00	-0.50
4	27/03/2010 11:00	2.537	17.463	3143.34	0.448	4500	0	1	4736.84	0.257437071	1356.66	1356.66	736204.96	16.92	-0.45
5	27/03/2010 12:00	3.452	16.548	2978.64	0.229	9000	600	1	10105.26	0.549199085	6021.36	6021.36	757881.85	25.47	0.37
6	27/03/2010 13:00	4.09	15.91	2863.8	0.229	9000	600	1	10105.26	0.549199085	6136.2	6136.2	779972.17	34.17	0.37
7	27/03/2010 14:00	4.373	15.627	2812.86	0.573	9000	600	1	10105.26	0.549199085	6187.14	6187.14	802245.88	42.95	0.03
8	27/03/2010 15:00	4.513	15.487	2787.66	0.721	9000	600	1	10105.26	0.549199085	6212.34	6212.34	824610.30	51.76	-0.12
9	27/03/2010 16:00	4.382	15.618	2811.24	0.765	9000	600	1	10105.26	0.549199085	6188.76	6188.76	846889.84	60.54	-0.16
10	27/03/2010 17:00	11.02	8.98	1616.4	0.426	9000	600	1	10105.26	0.549199085	7383.6	7383.6	873470.80	71.01	0.17
11	27/03/2010 18:00	9.66	10.34	1861.2	1.092	9000	600	1	10105.26	0.549199085	7138.8	7138.8	899170.48	81.13	-0.49
12	27/03/2010 19:00	7.23	12.77	2298.6	0.765	9000	600	1	10105.26	0.549199085	6701.4	6701.4	923295.52	90.64	-0.16
13	27/03/2010 20:00	5.862	14.138	2544.84	0.874	0	0	0	0.00	0	-2544.84	-2799.324	913217.95	86.67	-0.87
14	27/03/2010 21:00	5.283	14.717	2649.06	0.710	0	0	0	0.00	0	-2649.06	-2913.966	902727.67	82.54	-0.71
15	27/03/2010 22:00	5.132	14.868	2676.24	0.208	0	0	0	0.00	0	-2676.24	-2943.864	892129.76	78.36	-0.21
16	27/03/2010 23:00	5.077	14.923	2686.14	0.481	0	0	0	0.00	0	-2686.14	-2954.754	881492.65	74.17	-0.48
17	28/03/2010 00:00	4.853	15.147	2726.46	0.306	0	0	0	0.00	0	-2726.46	-2999.106	870695.87	69.92	-0.31
18	28/03/2010 01:00	4.628	15.372	2766.96	0.240	0	0	0	0.00	0	-2766.96	-3043.656	859738.71	65.60	-0.24
19	28/03/2010 02:00	4.454	15.546	2798.28	0.164	0	0	0	0.00	0	-2798.28	-3078.108	848657.52	61.23	-0.16
20	28/03/2010 03:00	4.27	15.73	2831.4	0.164	0	0	0	0.00	0	-2831.4	-3114.54	837445.17	56.81	-0.16

Figure 6 Grid-tied micro-CHP system Excel simulation model

Battery assisted grid-tied

In this case the surplus electrical energy is stored in a Li-Ion battery rather than being exported into the grid. This has several advantages such as electricity bill savings and better energy security, however capital costs are higher. Detailed analysis on economics provided below.

	A	B	C	D	E	F	J	K	L
1		Temp	Solar irradiation	set point temp	Heat loss (W)	Electrical demand	Energy Generated by CHP		
2	Date	deg C	W/m^2	20	180	kWh	Heat, Wh	Electrical, Wh	On/Off
3	27/03/2010 10:00	1.709	412	18.291	3292.38	0.50	0	0	0
4	27/03/2010 11:00	2.537	446	17.463	3143.34	0.45	4500	0	1
5	27/03/2010 12:00	3.452	446	16.548	2978.64	0.23	9000	600	1
6	27/03/2010 13:00	4.09	412	15.91	2863.8	0.23	9000	600	1
7	27/03/2010 14:00	4.373	344	15.627	2812.86	0.57	9000	600	1
8	27/03/2010 15:00	4.513	250	15.487	2787.66	0.72	9000	600	1
9	27/03/2010 16:00	4.382	141	15.618	2811.24	0.76	9000	600	1
10	27/03/2010 17:00	11.02	43	8.98	1616.4	0.43	9000	600	1
11	27/03/2010 18:00	9.66	0	10.34	1861.2	1.09	9000	600	1
12	27/03/2010 19:00	7.23	0	12.77	2298.6	0.76	9000	600	1
13	27/03/2010 20:00	5.862	0	14.138	2544.84	0.87	0	0	0
14	27/03/2010 21:00	5.283	0	14.717	2649.06	0.71	0	0	0
15	27/03/2010 22:00	5.132	0	14.868	2676.24	0.21	0	0	0
16	27/03/2010 23:00	5.077	0	14.923	2686.14	0.48	0	0	0
17	28/03/2010 00:00	4.853	0	15.147	2726.46	0.31	0	0	0

	M	N	O	P	Q	R	S	T	U	V
1	CHP Inputs			Thermal Energy Storage			Energy generated	Total El generated	Electrical Energy Storage	
2	Fuel Input,W	Fuel Price	Heat-Demand	Energy In/Out Wh	Buffer,kJ	Temp, C	Wh	Wh	Charging/Discharging	Buffer, Wh
3	0.00	0	-3292.38	-3292.38	731321	15.00	1225.98	1225.98	723.55	[illegible]
4	4736.84	0.25743707	1356.66	1356.66	736205	16.92	1327.15	1327.15	879.33	791.398
5	10105.26	0.54919908	6021.36	6021.36	757882	25.47	1327.15	1927.15	1697.78	2319.
6	10105.26	0.54919908	6136.2	6136.2	779972	34.17	1225.98	1825.98	1596.61	3756.34
7	10105.26	0.54919908	6187.14	6187.14	802246	42.95	1023.63	1623.63	1050.21	4701.53
8	10105.26	0.54919908	6212.34	6212.34	824610	51.76	743.92	1343.92	623.04	5262.26
9	10105.26	0.54919908	6188.76	6188.76	846890	60.54	419.57	1019.57	255.00	5491.7
10	10105.26	0.54919908	7383.6	7383.6	873471	71.01	127.95	727.95	301.98	5763.55
11	10105.26	0.54919908	7138.8	7138.8	899170	81.13	0.00	600.00	-492.24	5271.31
12	10105.26	0.54919908	6701.4	6701.4	923296	90.64	0.00	600.00	-164.57	5106.74
13	0.00	0	-2544.84	-2799.324	913218	86.67	0.00	0.00	-873.79	4232.95
14	0.00	0	-2649.06	-2913.966	902728	82.54	0.00	0.00	-709.96	3522.99
15	0.00	0	-2676.24	-2943.864	892130	78.36	0.00	0.00	-207.53	3315.47
16	0.00	0	-2686.14	-2954.754	881493	74.17	0.00	0.00	-480.59	2834.88
17	0.00	0	-2726.46	-2999.106	870696	69.92	0.00	0.00	-305.83	2529.06

Figure 7 Excel model for Solar PV and battery assisted system.

Column T – "Charging/Discharging" - shows the difference between generated electricity and household demand. Positive values correspond to the surplus electrical energy and show the amount of energy used for battery charging. Negative values correspond to deficit and show the amount of energy used to cover household's electrical demand (from the battery storage or imported from the grid.

Column U – "Electrical Energy Storage Buffer" – shows the amount of energy stored in the electrical battery.

Logic	
IF column T ("Charging/Discharging") is negative AND the amount of energy in the battery bellow lower limit (1000Wh)	THEN $U_{cell}=U_{cell-1}$
IF column T ("Charging/Discharging") is negative AND the amount of energy in the battery above lower limit (1000Wh)	THEN $U_{cell}=U_{cell-1}+T_{cell}$, ($T_{Cell}<0$)
IF column T ("Charging/Discharging") is positive	THEN $U_{cell}=U_{cell-1}+T_{cell}$*(90%efficiency)

Column W – "Comparison with actual electrical demand" – shows the amount of electrical energy imported from the grid to cover household demand. Also, next column T – explains for how many hours the household is in energy deficit.

Solar PV battery assisted grid-tied/off-grid system

Column C – shows an hourly average global solar irradiance on a fixed plane in W per meter squared for planes with inclination of 42^0.

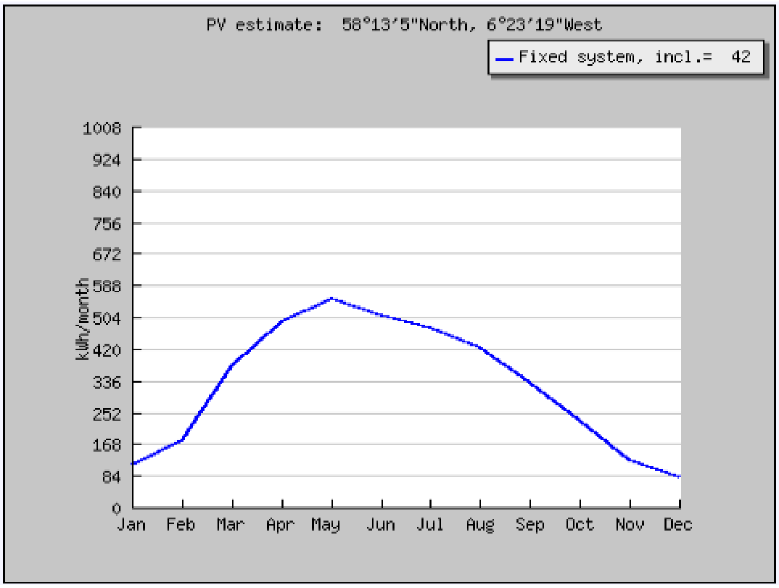

Figure 8 PV System Output estimate (PVGIS)

In addition to energy generated by the CHP system this model includes the energy generated by the Solar PV system (Column S) and combine output is shown in Column T.

Similarly, to the previous models, the energy (thermal and electrical) produced by the CHP system is used to cover the household demand first. The surplus thermal energy will be stored in the thermal energy storage tank and electrical energy will be stored in the Li-Ion battery.

According to the data received from the model this system might require a larger electrical storage device. Tesla Powerwall 2 with integrated inverters was chosen for this application. (See chapter 6.5.3 for details)

5.5 Simulation Model Analysis

Grid tied system

Considering the system specifications and assumptions listed above, the 19566kWh of thermal energy and 1183.8kWh of electrical energy will be generated by the CHP system over the period of one year.

This mean that the heat energy demand of the household will be covered 100% by the CHP system, with 2375 out of 8760 hours a year (or 27.11%) when the system is ON.

As the primary output of this system is thermal energy and electrical energy is a secondary output (heat-to-electricity ratio 9/1), it was beneficial to observe the dynamics and final output of electrical energy generation. For the grid-tied system with the standard specifications the electrical energy generated by the system could cover 1183.8kWh out of 3889kWh of the annual demand (30.4%). As there will be periods when electrical output of the system will exceed the household demand, some energy might be exported to the grid. According to the simulation model, the exported energy will be 419.6kWh a year.

To cover the household electrical energy deficit when the CHP is not operating and is not generating enough power, some energy will be imported from the grid. In absolute values, the electrical energy import will be 3125.7kWh (80.4% of the total demand) and will be required for 7365 hours per year.

The graph below represents the electrical energy import/export trends over a period of 5 days from 27 March to 31March.

Figure 9 Electrical energy export/import trends

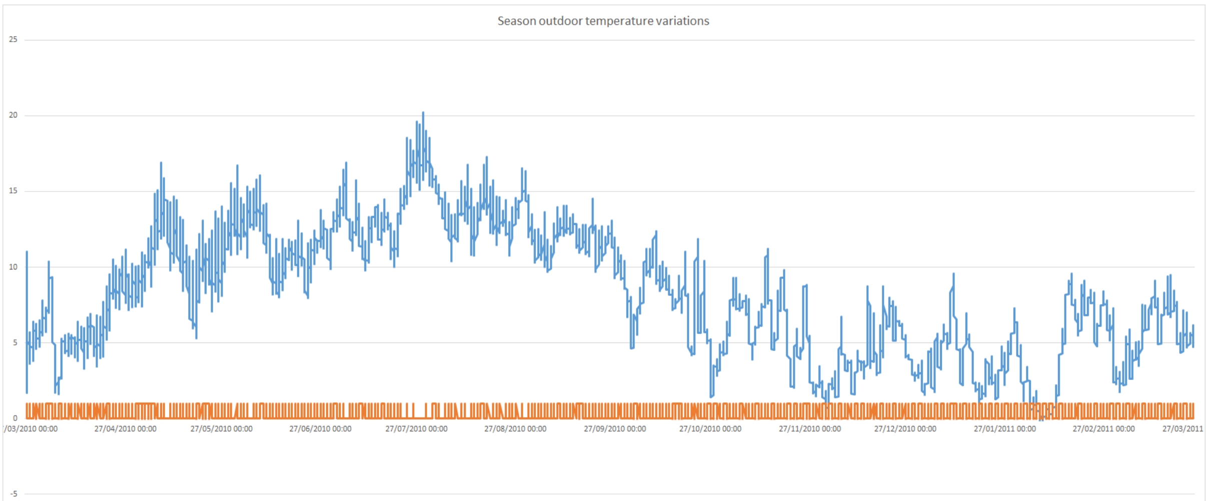

Figure 10 Weather variation graph and system ON/OFF hours, annual outdoor temperature variations

Due to a higher outdoor temperature in the summer, the system required less energy to bring the indoor temperature to the comfort level, thus the intervals between the system “ON” times are be larger. This will lead to an increase of the hours when additional electrical energy (import) will be required. Alternatively, solar PV system can cover electrical energy shortage over the warmer periods (See 0 page 26).

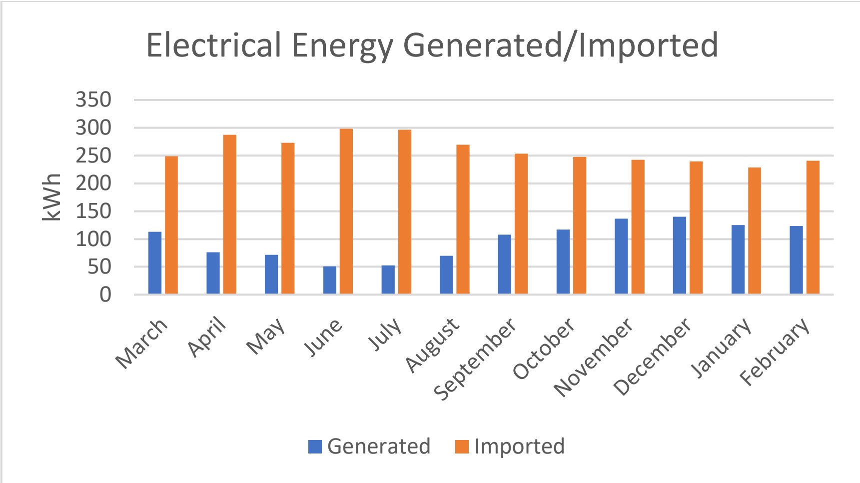

Figure 11 Electrical energy generated/imported by month.

Summary		
Average annual temperature	8.4	deg C
Max heat loss (entire building)	3611.34	W
Max electrical load	7	kW
Average TES temperature	64.38	deg C
Total Heat Energy generated	19566	kWh
Total Electrical Energy generated	1183.8	kWh
Total Electrical Energy imported	3125.682	kWh
Total Electrical Energy exported	419.577	kWh
Hours in deficit (importing)	7365	h/year
Total fuel input	21841.89	kWh
Fuel input, kg	4748.237986	kg
Fuel costs (wood pellets)	1187.06	£
CHP running time	2375	h/year
Grid electricity cost	531.37	£

Table 5 Summary for Grid tied system

Battery assisted grid-tied system

The main benefit of the battery assisted system is that a low-value electrical energy generated during the CHP system "ON" periods, can be stored and used later when demand is high, thus providing additional benefits on electrical energy savings and reducing the number of hours of electrical energy import.

Total thermal energy generation and fuel input will be the same as in previous scenario; however annual electrical energy import will be reduced by 376.52kWh or 12.04%.

According to the data from simulation model, the maximum electrical storage capacity of 3.2kWh is required.

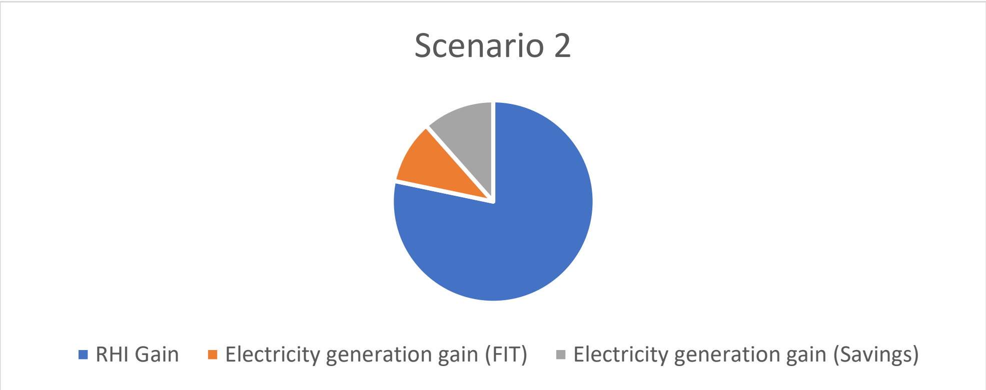

Figure 12 Pie chart for battery assisted grid-tied system

Summary		
Average annual temperature	8.4	deg C
Max heat loss (entire building)	3611.34	W
Max electrical load	7	kW
Average TES temperature	64.38	deg C
Total Heat Energy generated	19566	kWh
Total Electrical Energy generated	1183.8	kWh
Total Electrical Energy imported	2749.163	kWh
Total Electrical Energy exported	--	kWh
Hours in deficit (importing)	6278	h/year
Total fuel input	21841.89	kWh
Fuel input, kg	4748.237986	kg
Fuel costs (wood pellets)	1187.06	£
CHP running time	2375	h/year
Grid electricity cost	467.3577	£

Table 6 Summary for Battery assisted grid-tied system

Solar PV battery assisted grid-tied/off-grid system

Additional, to the energy generated by the CHP system, the electrical energy produced by the PV system is 3291.5kWh or 73.54% of the total generation.

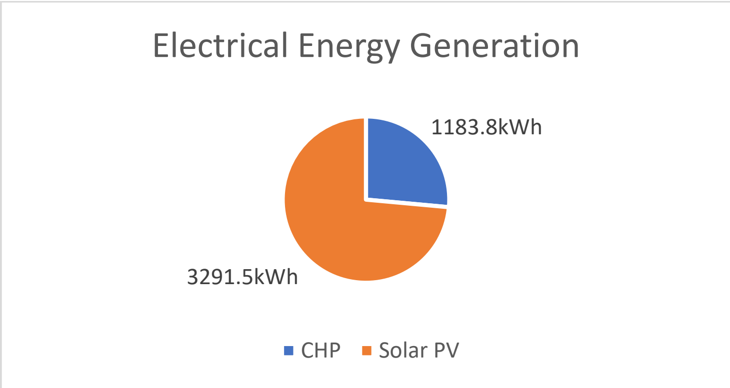

Figure 13 Pie chart for electrical energy generation

As more energy is being produced, this system requires higher capacity energy storage. For this model we were using Tesla Powerwall 2 Li-Ion electrical energy storage bank with 13.5 kWh capacity and integrated power inverter.

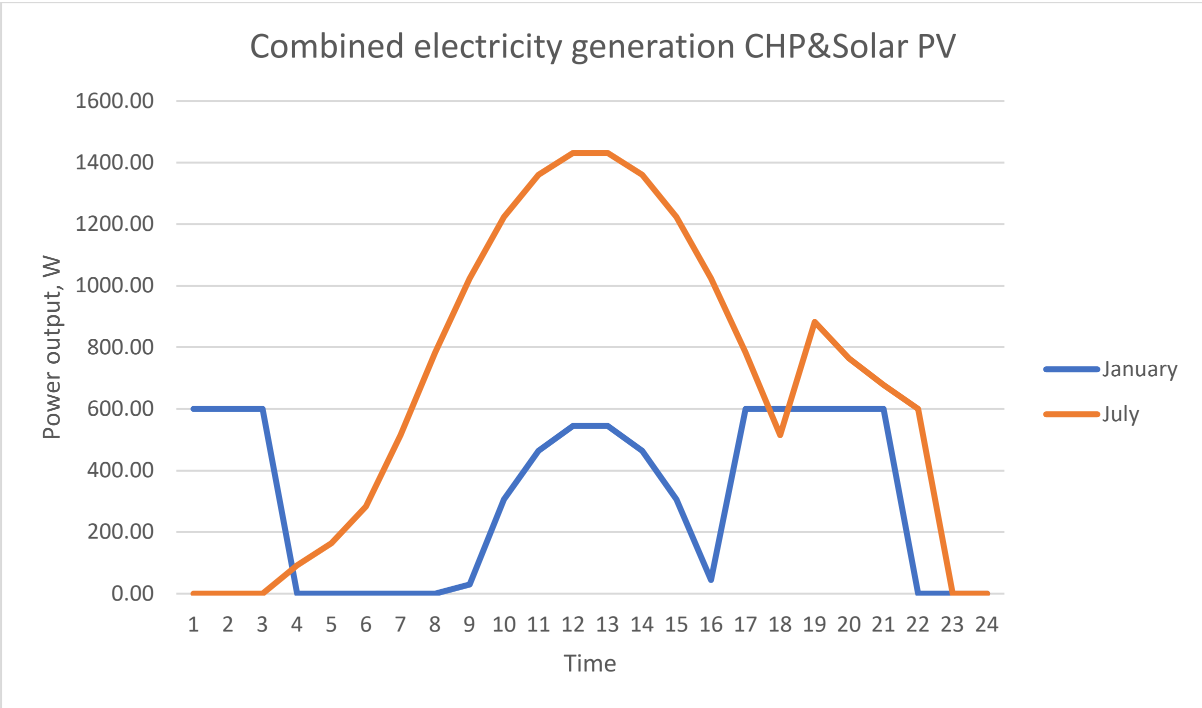

Figure 14 Power produced with CHP and solar over 24 hrs.

Considering the solar irradiation data and technical characteristics of the CHP and solar PV systems, a new simulation model was produced which showed that the electrical energy import will be reduced by 83.22% from 2749.16kWh to 461.28kWh a year. However, it is still required to have the grid connection to cover the household electrical energy demand.

The trend of the combined electrical energy generation against the energy import is shown below. Electrical energy deficit occurs during the winter months as solar irradiation levels are lower and the solar PV system cannot cope with increasing demand.

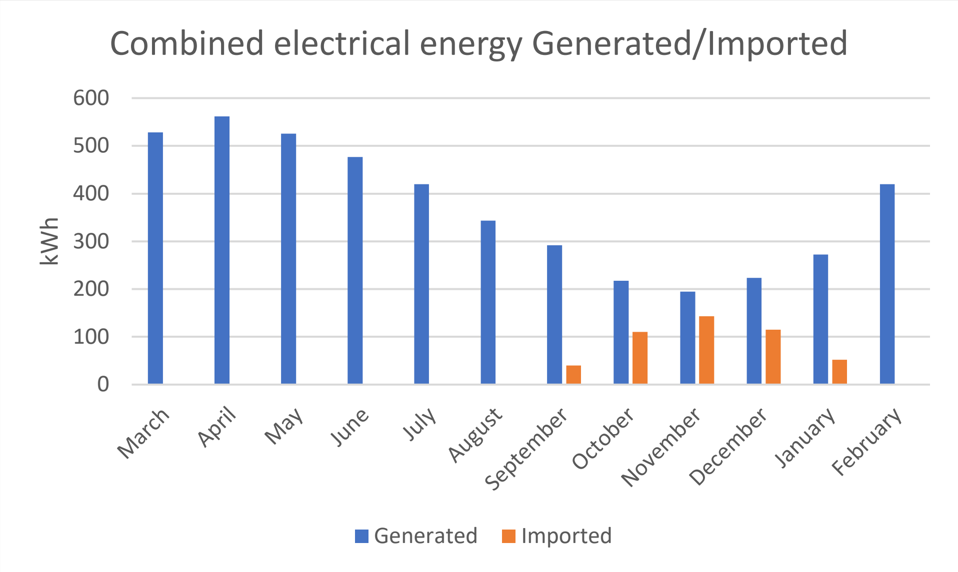

Figure 15 combined electrical energy generation vs energy import

Solutions to resolve this issue were proposed:

Increase the number of solar panels and/or electrical storage capacity.
This solution will require a total of 60 panels or 44 panels and 2 Tesla Powerwall energy storage units to be installed in order to provide fully grid independent system. Additional benefits can be received from the electrical energy export to the grid, however capital costs will be increased significantly.

Install a micro-scale vertical axis wind turbine.
2kW wind turbine will provide enough energy during the winter months (which are usually windier) to cover the energy deficit. The vertical axis wind turbine is chosen as it is more suitable for residential areas where the wind is more turbulent and planning permission of placing a new device is an issue.

Run CHP system for extended periods from September to January
Increased fuel bill will be covered by the RHI tariff and by the electrical energy savings. This solution doesn't require additional capital expenditures.

Increase the Stirling Engine power output to 1.4kW and electricity-to-heat ratio to 1:6.
According to the simulation model, the engine with power output of 1400 Watts will be able to cover the electrical energy requirements for a single household and will bring additional benefits due to a Microgeneration scheme FIT and electricity export.

Summary		
Average annual temperature	8.4	deg C
Max heat loss (entire building)	3611.34	W
Max electrical load	7	kW
Average TES temperature	64.38	deg C
Total Heat Energy generated	19566	kWh
Total Electrical Energy generated	1183.8	kWh
Total Electrical Energy imported	461.128	kWh
Total Electrical Energy exported	649.522	kWh
Hours in deficit (importing)	1330	h/year
Total fuel input	21841.89	kWh
Fuel input, kg	4748.2	kg
Fuel costs (wood pellets)	1187.06	£
CHP running time	2375	h/year
Grid electricity cost	78.3918	£
RHI Gain	1318.75	£
Electricity generation gain (FIT)	298.94	£
Electricity generation gain (Export)	1093.47	£
Electricity generation gain (Savings)	3428.78	kWh
Electricity generation gain (Savings)	582.89	£

Table 7 Summary for Solar PV battery assisted grid-tied/off-grid system

4. Technologies suitable for electrical generation

4.1 Prime Movers

Gas Turbines

The Gas Turbines or a Combustion Turbines works on a Bryton cycle principle. A compressor is coupled to a turbine with a combustion chamber in between. The added energy generates a high-temperature gas flow (usually air) which enters the turbine, expands down to exhaust pressure, producing mechanical energy (rotation) on a shaft and creating the work output. (Eastop & McConkey, 1993)

These systems are used for gas-powered power plants, combined cycle power plants, jet engines and microturbines. Gas turbines can be powered by petrol, LPG, syngas, propane, etc.

Microturbines are the common solution for the small cogeneration units. These are simpler than Internal Combustion Engines and claim to have an overall efficiency of up to 100% when used in a combined heat and power cycle (HHV, e.g. NeoTower Living).

The Bryton cycle micro-CHP cogeneration units available on the market are:

1. Enertwin from MTT
2. TwinGen from Samad Power

The core of the **EnerTwin** micro-CHP is a recuperated micro turbine which was developed based on turbocharger components from the automotive industry and can reach the electrical power output of 3kW with 16% efficiency. The MTT promises that their microturbines are very robust, require virtually no maintenance, with low vibration and low noise operation, guarantying long life.

This system can be powered by natural gas, however, versions that run on domestic fuel oil, LPG and biogas are in development. Modulated power outputs are:

- Electrical 1-3.2kW
- Thermal 6-15.6kW

Power-to-heat ratio 20%, Electrical efficiency 16%, Total efficiency 94%.

Figure 16 EnerTwinn (Courtesy of Micro Turbine Technology)

Another solution is a TwinGen micro-CHP module from Samad Power. This product is still in development stage, but it has a great potential on the micro CHP market. The small-scale gas turbine has been designed to be integrated with traditional boilers, just replacing the burner and a fan while leaving most of the other internal and external component parts in place without any significant changes. Power output is:

- Net Electrical: 1-2kW
- Net Thermal: 3-18kW
- Overall Efficiency: 90% (LHV)

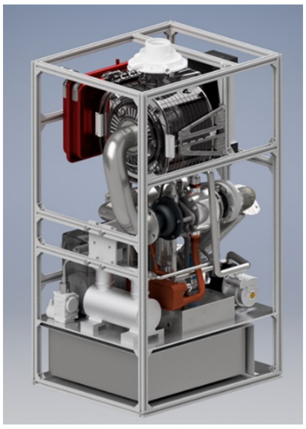

Figure 17 TwinGen (Samad Power)

Advantages

- Fast Start-up with good response times
- Compact size
- Simple design

Disadvantages

- High operating speed
- Reduced power output at higher ambient temperatures

Rankine Cycle Machines

In Rankine power cycle water is converted into high-pressure steam in a boiler or steam generator. This high-pressure steam is used to drive the turbine or other prime movers connected to the generator. Because the steam cannot be transported to the boiler efficiently to get additional temperature, it is converted into a liquid first in condensers or heat exchangers, and then water can be delivered to the boiler using a circulating feed pump. (Makhamov, 2011)

The typical Rankine cycle machines are:

- Reciprocating piston machines
- Steam turbines

Steam turbines are the most popular solution for large-scale power plants. The water is converted into high-pressure superheated steam which expands in high-pressure turbine. Then it can be used to drive low-pressure turbine or just condensed back to the liquid state.

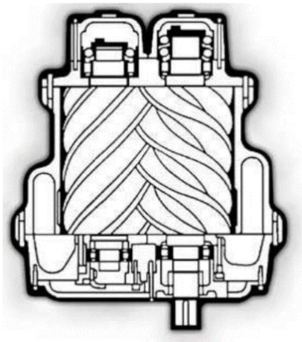

Figure 18 Organic Rankine Cycle

- Scroll or screw mechanism machines

These can be used for micro-CHP applications due to their size and control options. However, water needs to be converted into the high-pressure steam, which is not always possible with existing heating systems. To operate efficiently this engine requires a high-temperature heat exchanger or steam generator. Another downside is it low maintenance intervals because of corrosion.

Rankine cycle micro-CHP products are represented by the UK based Flow Group company cogeneration boilers. This company has developed a scroll expander domestic micro CHP platform that can be used to generate electricity while heating the home. The technical characteristics of this module states that the electric efficiency is 10% but overall efficiency is 90%!

At present, this is the only not-Fuel-Cell based system which is eligible for the micro-CHP Feed-in-Tariff under the Microgeneration Certification Scheme (MCS). However, this micro CHP system is available for the Flow Energy company customers only and will not be considered in the market analysis review.

4.2 Internal Combustion Engines (ICE): Diesel/Otto

Internal combustion engines can be adapted for different liquid fuel types: petrol, diesel, LPG/LNG, biofuels, syngas etc.

Four stroke engines with ignition sparks built in the head of the cylinders and powered by the natural gas are usually used for domestic micro-CHP systems (Viessmann, Baxi Dachs, Vaillant Ecowill, Energimizer, etc.). The average electrical efficiency for micro-CHP systems based on ICE technology varies from 15% to 25%, with a total efficiency being between 80% and 90%.

Large truck or tractor modified engines can be used for large domestic or small commercial applications producing 15kW-50kW power output (ESPE).

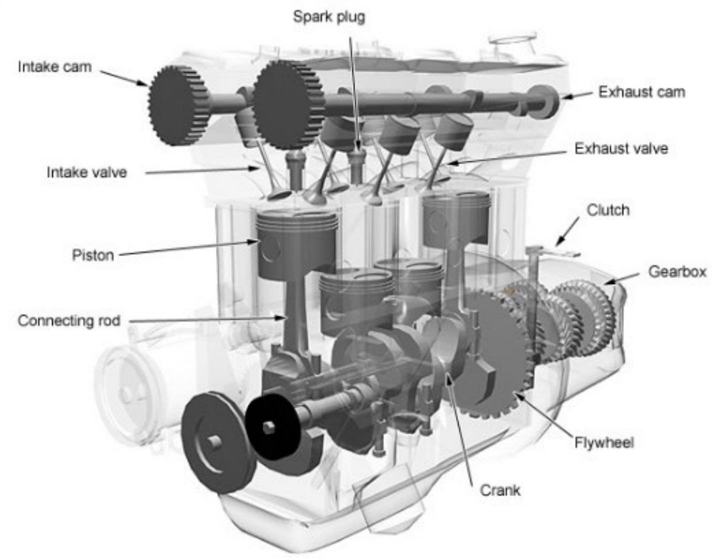

Figure 19 Internal Combustion Engine. (Pinterest)

ICE technology is widespread in the automotive industry. The main advantage of the internal combustion is its rapid variation in power output, which can be controlled by changing the fuel supply rate. Efficiencies can be increased by recovering heat from exhaust gases and the engine cooling system.

Disadvantages of the ICE:

- low maintenance intervals
- high noise level
- need for constant fuel supply.

4.3 Stirling Engines

The Stirling engine is an external combustion heat engine working on a closed-loop regenerative cycle. The gaseous working fluid is sealed inside the engine, allowing some advantages over the conventional steam engines. This working fluid undergoes the same processes as any heat cycle: cooling, compression, heating and expansion. During the expansion process, the useful power output is generated depending on the temperature difference between the hot and the cold pistons as well as the total mass of the working fluid. (Beith, 2011)

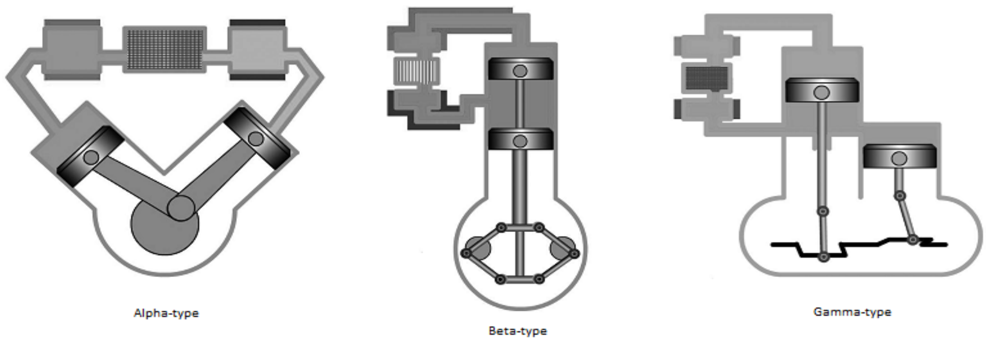

Figure 20 Types of Stirling Engines. (Makhamov, 2011)

Stirling engines can be connected to any heat sources or existing heating systems, thus reducing the total price of a micro CHP installation.

Other advantages are:

Simple design	Fewer moving parts than internal combustion engine or steam turbine. No valves are needed.
Maintenance	Service intervals are much larger
Safety	Low risk of explosion due to working fluid overpressure.
Quiet operation	Due to no explosive combustion taking place.

The leading producer of Stirling Engine micro CHP systems is MEC (Microgen) who produce a Microgen engine with an electrical efficiency of 26% and maximum power output of 1.05kW.

Figure 21 The MEC Stirling Engine. (Microgen Engine Corp.)

AnotherCompany, **Qnergy** uses a similar design engine for their SmartBoiler micro-CHP system. Qnergy's free piston Stirling engine (FPSE) generator requires a temperature differential across the engine which cause the helium inside the engine to expand and contract, which in turn drives a linear reciprocating motion of the piston. The FPSE directly converts the reciprocating motion of the piston into electrical power using the integral linear alternator. The unit is working on LNG/LPG gas and requires annual inspection and testing as a conventional gas boiler. This engine has fewer moving parts than traditional kinematic Stirling engines or conventional ICE, and has no direct-contact points that cause wear and require lubrication. Thus, FPSE is a maintenance-free technology that offers long-life performance.

Electrical power output varies from 2.8kW to 7.2kW.

The overall efficiency is claimed to be 99%.

Figure 22 Qnergy PCK80 FPSE

Qnergy's PCK80 FPSE generator can be bought separately and combined with any available heat source: combustible liquid/gaseous fuels, wood/paper fuels, bio fuels and other sources of high-grade waste heat.

The Austrian company OekoFen have integrated the MEC Stirling engine and thermal energy storage tank into a wood pellet biomass boiler. The integration of a pellet burner, Stirling module and a heat accumulator results in optimisation of the operating time, space-saving construction and the reduced heat losses. This means that a greater quantity of sustainable electricity can be generated at the same time as the heat accumulator is loaded with heat. The heat accumulator serves as a thermal energy store, which separates the heat generation mechanism from the actual heat consumption. Therefore, the Smart_e can also be operated when electricity is required but there is no heat demand in the building.

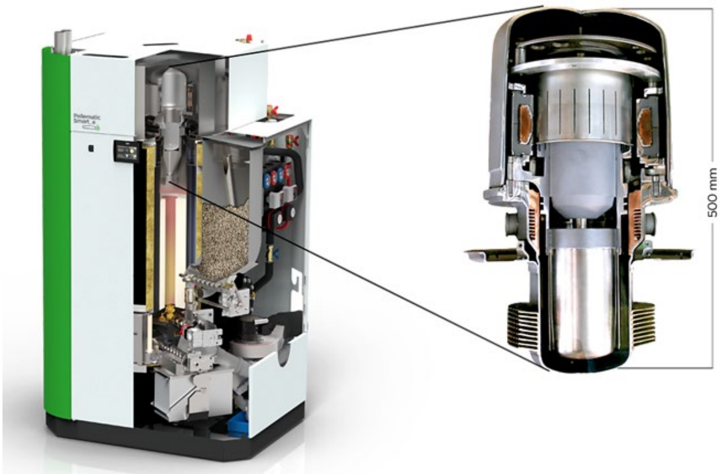

Figure 23 OkoFen Smart_E Pellet

4.4 Fuel Cells

Fuel cells convert chemical energy into electrical energy. The primary purpose of fuel cells is to store the energy, but during the energy conversion process, it produces some waste heat energy which can be captured and used for air or water heating.

Fuel cells operate like a rechargeable battery except that a constant fuel supply is needed and tend to be more efficient in extracting energy from hydrogen than combustion (see Table 1. below). The reaction is noise-free thus making fuel cells more attractive for domestic applications than internal combustion engines.

Fuel cells need a constant fuel supply which is not always possible in remote areas and, in the case of hydrogen-powered fuel cells, the supplied hydrogen should be free of carbon which can damage the membrane. Also, electrolysers required for hydrogen production and hydrogen storage tanks are currently very expensive for domestic use.

4.5 Comparison Table

Technology	Electrical Efficiency	Electricity/ heat ratio	Advantages	Disadvantages	Cost
Gas micro-turbine	16-20%	1:6	Fast start-up, quick response. Compact size. Simple design. Low emissions.	High operating speed. Reduced power output at higher ambient temp.	Med
Steam turbines	5-30% (micro CHP)	1:5-1:9	Any fuel types	Slow start-up. Risk of explosion due to overpressure. High noise level	Low
Internal Combustion Engine	15-25%	1:3	Proven technology. Fast start-up, easy control	Frequent maintenance. High noise level. High emissions.	Fairly Low
Stirling Engine	15-45%	1:6	Low noise level. Large maintenance intervals. Any fuel type	Slow start-up and response time Low commercialisation status	Med
Fuel Cells	30-63%	1:1	Low noise. Best efficiency	Low durability Flammable Expensive fuel supply infrastructure	Very High

Table 8 Comparison of micro CHP Technologies.

5. Energy Storage

Electrical and heat energy production and consumption are not constant – sometimes more energy will be produced than is needed so it is expedient to store any excess energy and use it when it is more demanded.

Several energy storage technologies can be used in a micro-CHP system. These need to be compact, inexpensive and able to provide the constant power supply for up to 10 hours.

There are three types of systems suitable for domestic applications:

Technology	Application
Electrochemical	Rechargeable Batteries Fuel Cells
Chemical	Biofuels Hydrogen
Thermal	Liquids Molten Salts Solids

5.1 Electrochemical

Rechargeable Batteries

The most popular solution for electrical energy storage is the use of rechargeable batteries. The key advantage is that the stored chemical energy is directly converted into electrical energy and its efficiency is not limited by the Carnot-cycle characteristics.

5.2 Chemical

The products of chemical reactions such as a syngas from pyrolysis[1], hydrogen from electrolysis and bioethanol from fermentation can be defined as energy carriers in the energy production chain. These fuels can be produced during off-peak periods and can be burned or used in internal combustion engines or fuel cells when demand is high.

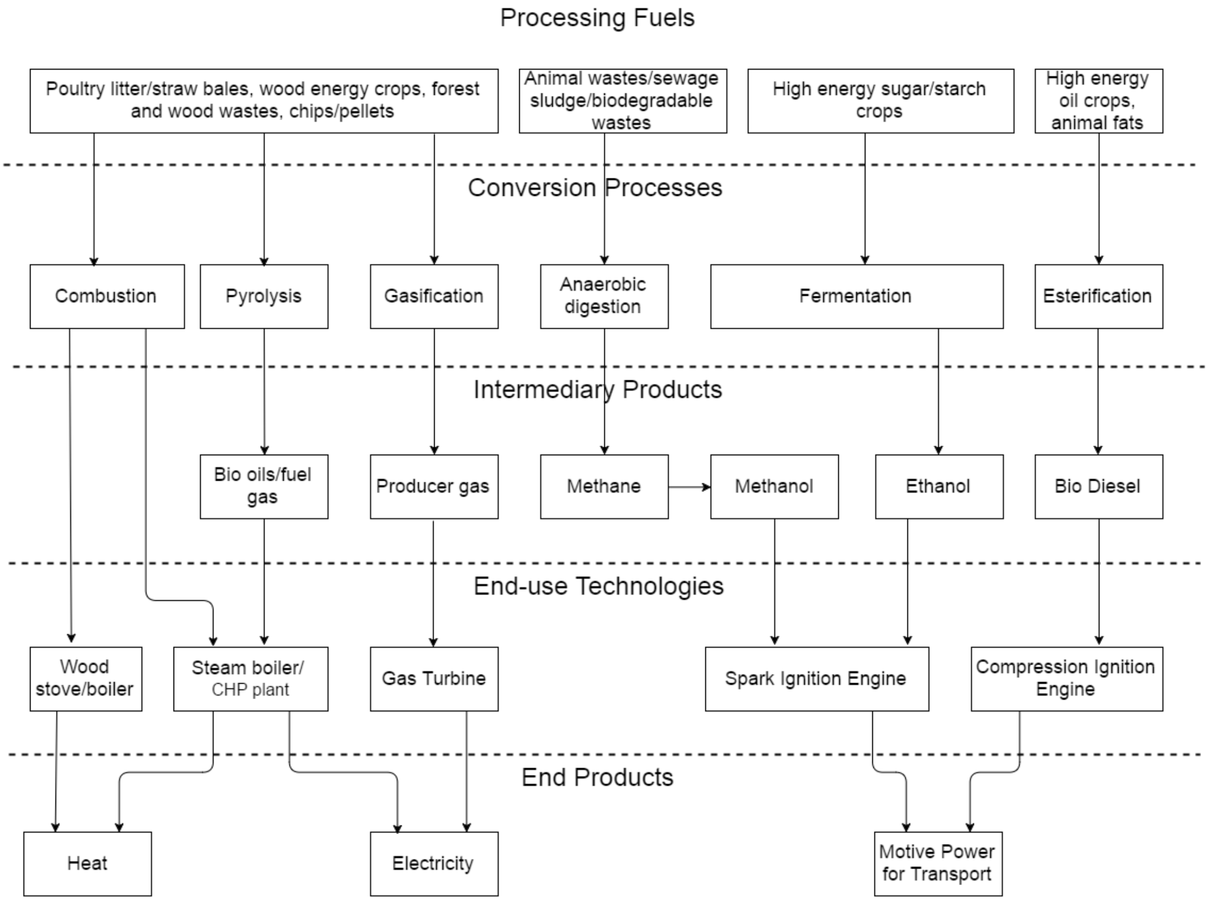

Figure 24 Biomass Conversion Process. (Glasgow Caledonian University)

These substances require storage facilities (tanks, compressors) and extra safety precautions to meet Health and Safety legislation.

Hydrogen has the highest energy density (per unit mass) and is also it is very flammable within the wide range of concentrations (4-75%), compared to 5-15% of methane. It is possible to liquify the hydrogen using cryogenic storage, but then only 30% of the energy can be recovered.

[1] the thermal decomposition of materials at elevated temperatures in an inert atmosphere. It involves the change of chemical composition and is irreversible.

5.3 Thermal

Low-temperature Thermal Energy Storage (TES) can be used for space heating, and high-temperature TES can be used in power plants or industrial processes. Heat energy can be efficiently stored in insulated tanks using water or molten salts or in solids such as hot rocks, concrete or bricks.

The high efficiency of TES using water can be achieved due to its high specific capacity - about 4.2 kJ/kgK.

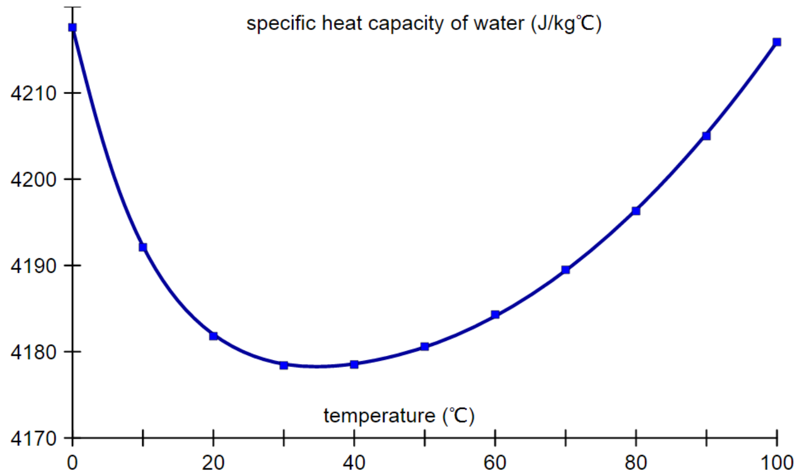

Figure 25 Specific heat capacity of water.

The temperature at which water boils increases with pressure. An example of TES for domestic applications is a buffer tank in a heating system:

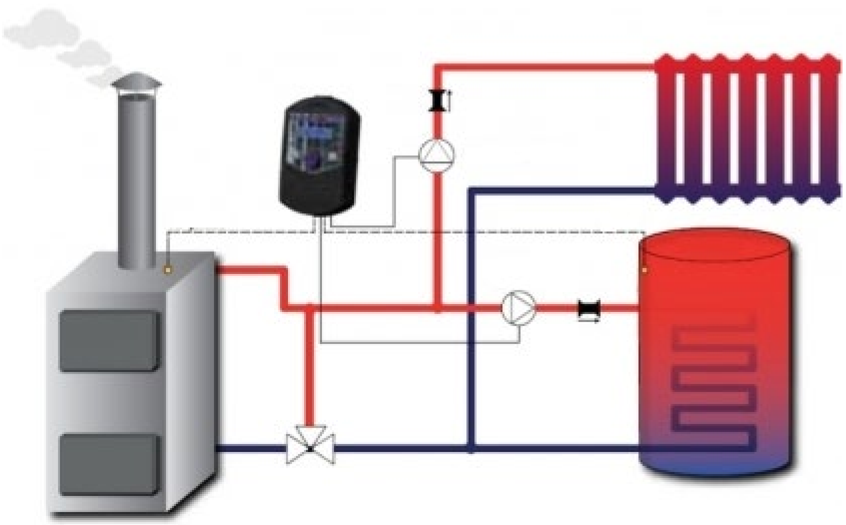

Figure 26 Domestic Heating System. (TECH Controllers)

Thermal losses within the system can be minimised by insulating the pipes and storage tank leading to a total efficiency of up to about 95%.

Molten Salt Storage

Compounds used for TES are nitrites or fluorides mixtures. The specific heat capacity of these substances is about one-third of the water, but the operating temperature range is much wider: e.g. for “Hitec XL” the freezing point is 120^{0}C, and upper temperature is 500^{0}C. Some fluoride compound storage media (Lithium/Sodium/Magnesium fluoride, LiF/NaF/MgF_2) have a melting point of 632^{0}C. These mixtures are chemically stable and can be stored in special vessels. (Dr. Ter-Gazarian)

The high-temperature molten salt TES systems are suitable for large scale applications such as concentrated solar power (CSP) plant systems or industrial applications where heat energy can be stored for days or even weeks.

Hot Rocks/Concrete/Bricks (Solids)

The table below shows the thermal properties of some solids:

Substance	Specific Heat, c_p (kJ/kg · K)	Density, ρ (kg/m^3)	Thermal Conductivity, κ (W/m · K)
***Selected Solids*, 300K**			
Aluminium	0.903	2700	237
Coal, anthracite	1.260	1350	0.26
Copper	0.385	8930	401
Granite	0.775	2630	2.79
Iron	0.447	7870	80.2
Lead	0.129	11300	35.3
Sand	0.800	1520	0.27
Silver	0.235	10500	429
Soil	1.840	2050	0.52
Steel (AISI 302)	0.480	8060	15.1
Tin	0.227	7310	66.6

Table 9 Properties of Selected Solids. (Lak, 2015)

The specific heat capacities of the above are much lower than of water, but maximum temperature can be as high as 1200^{0}C, therefore, providing greater overall volumetric capacity.

The well-known applications of hot rock TES are:

- Domestic wood-fired stoves
- Electric thermal storage heaters, where night tariff low-cost electricity is used to heat up well insulated ceramic brick heaters, store heat and released it during the day.

6. Financial Projections

6.1 Financial Model Description

Financial projections were prepared for all three scenarios. System specifications, energy output, fuel prices, fuel input and other variables were considered in the calculations.

Based on the information gathered during the research on the Fuel Supply Chain and Market Availability (see Deliverable DT1.3.1), the fuel prices and specifications can be summarised as follows:

Biomass Fuel Specifications		
Pellets made of 100% natural wood according to ISO 17225–2, class A1		
EN ISO 17225–2, class A1		
Calorific Value	>=16.5	MJ/kg
	4.6	kWh/kg
Bulk Density	600	kg/m^3
Moisture Content	10	%
Ash Content	0.7	%
Length	40	mm
Diameter	6	mm
Price	250	£/tonne
Price per kWh	0.054348	£/kWh

Heating Oil		
Calorific Value	10000	kWh/1000 litres
Price Scottish Fuels	615.2	£/1000 Litres
Price per kWh	0.06152	£/kWh
Electricity		
Price per kWh = £0.17 /kWh		

Table 10 Average Fuel Prices UK

Fuel prices and trends were also checked against the open market information and the UK Energy Statistics (DUKES, 2017).

According to the BEIS Microgeneration Scheme RHI tariff table announced on 28 February 2018, the current and future tariffs for biomass boilers and CHP systems are 6.74p per kWh of thermal energy generated.

All three scenarios (Grid-tied system, battery assisted system, off-grid system) were analysed. Accumulated Capital Expenditures and Operational Expenditures for each scenario were compared against annual income from RHI, FIT, electricity and heat savings as well as a surplus electrical energy export.

This made it possible to compare potential biomass micro-CHP system installation, existing oil-fired boiler heating system and new oil-fired boiler heating systems; produce informative break-even graphs, compare Return-on-Investments rate and calculate the system's payback times.

6.2 Financial Model Analysis

The system design is based on heating demand, with electricity being a by-product which can bring additional benefits. The heat generation values, fuel input and CO_2 emissions will be the same for all scenarios.

However, the system's electricity generation output will depend on the outside temperature variations, desirable internal temperature, and on the electrical system configuration. As an example, the total energy imported is different for all scenarios. For Scenario1 it is 3125.68kWh and for Scenario 3 (CHP+Solar PV) it is only 461.13kWh with the further possibility of the import reduction due to an installation of a higher rating Stirling Engine generator.

	Scenario 1	Scenario 2	Scenario 3	Units
Total Heat Energy generated	19566.00	19566.00	19566.00	kWh
Total Electrical Energy generated	1183.80	1183.80	1183.80	kWh
Total Electrical Energy imported	3125.68	2749.16	461.13	kWh
Total Electrical Energy exported	419.58	0.00	649.52	kWh
Hours in deficit (importing)	7365	6278	1330	h/year
Total fuel input	21841.89	21841.89	21841.89	kWh
Fuel input, kg	4748.24	4748.24	4748.24	kg
Fuel costs (wood pellets)	1187.06	1187.06	1187.06	£
CHP running time	2375.00	2375.00	2375.00	h/year
Grid electricity cost	531.37	467.36	78.39	£
Grid electricity CO2 emissions	1098.86	966.50	162.11	kgCO2e
Wood pellets CO2 emissions	277.39	277.39	277.39	kgCO2e
Oil-fired boiler CO2 emissions (NEW)	5610.21	5610.21	5610.21	kgCO2e
Oil-fired boiler CO2 emissions (OLD)	8041.30	8041.30	8041.30	kgCO2e
Oil-fired boiler fuel cost (NEW)	1399.65	1399.65	1399.65	£
Oil-fired boiler fuel cost (OLD)	2006.17	2006.17	2006.17	£
RHI Gain	1318.75	1318.75	1318.75	£
Electricity generation gain (FIT)	171.89	171.89	298.94	£
Electricity generation gain (Export)	21.99	0.00	1093.47	£
Electricity generation gain (Savings)	764.22	1140.74	3428.78	kWh
Electricity generation gain (Savings)	129.92	193.93	582.89	£
Total Gain	1642.54	1684.56	3294.05	£

Table 11 Simulation Results

The total gain from the RHI tariff and combined electricity FIT/export/savings is only 2.56% higher for battery assisted system compare to the grid-tied micro CHP system, while it is 100.54% higher for the combined micro CHP and Solar PV system.

6.3 Scenario 1 Analysis

Figure 27 below shows the comparison of the accumulated expenditure against accumulated income. The annual expenditures on fuel and maintenance were added to the total capital costs and compared with accumulated income from the heat and electricity generation. As a result, the payback time for the grid-tied micro-CHP system will be approximately 8.65 years and the ROI (Return-on-Investment) rate will be 11.56%

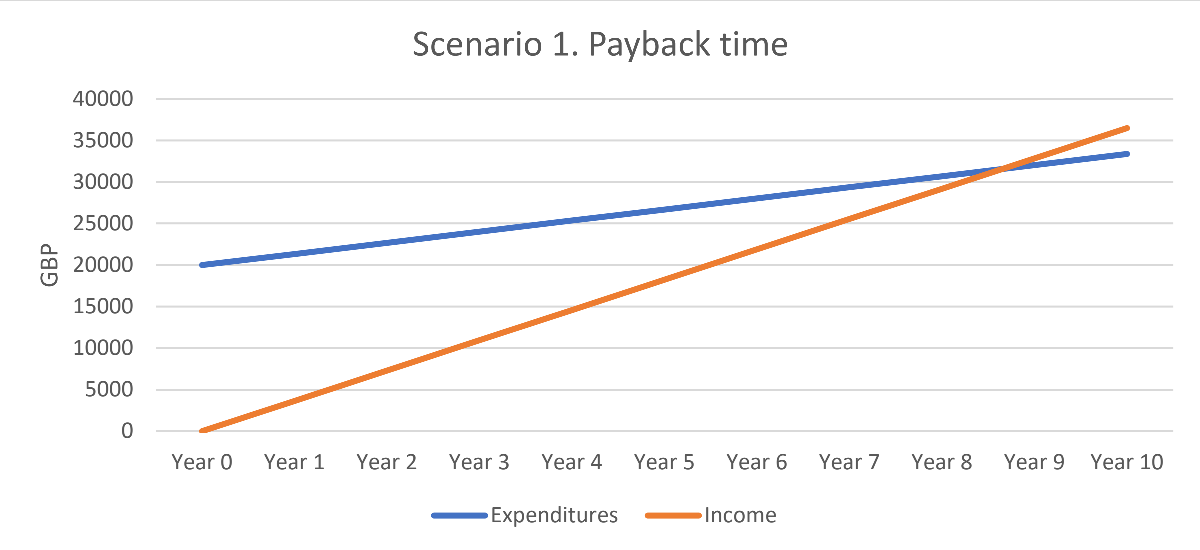

Figure 27 comparison of the accumulated expenditure against the accumulated income

Comparison with oil-fired boilers (new installation and existing heating system) shows that very high Capital Expenditure for a micro CHP system can be expected; however the gain from the heat generation through the Renewable Heat Incentives will cover the annual expenditures associated with the fuel and maintenance costs.

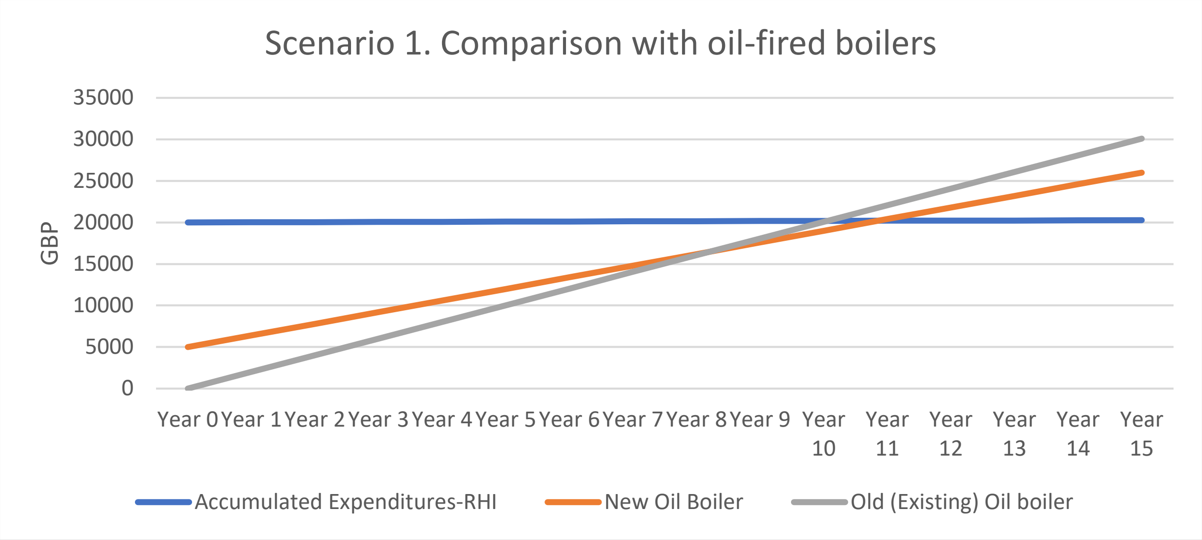

Figure 28 Scenario 1, comparison with oil-fired boilers

It is expected that after 10-11 years of operation, the accumulated expenditure of the oil-fired heating systems will be higher than of the micro CHP (this term can be even shorter if the oil prices increase).

However, if the cost of the electrical energy imported from the grid is also considered, then the amount of the total operational expenditure for the oil-fired heating system will be increased, while the gain from the electrical energy generation and savings for the micro CHP system will reduce the operational expenditure. Thus, the accumulated operational expenditure trends of the micro CHP will show a decreasing line, while the accumulated operational expenditure trend lines for oil-fired heating system will increase. The benefits of the micro CHP system after four years of operation are clearly seen on the graph below.

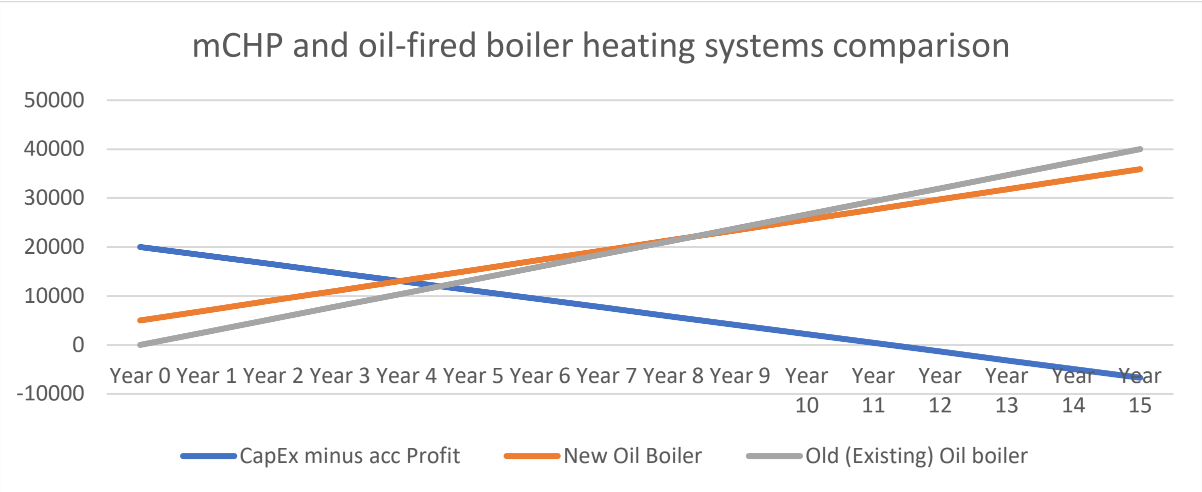

Figure 29 micro CHP and oil-fired boiler heating systems comparison

6.4 Scenario 2 Analysis

When supplementary energy storage battery is added to the system, additional benefits due to the electricity savings are possible, however capital expenditure is slightly higher. As a result, the payback time will be approximately 9.14 years and ROI will be 10.95%.

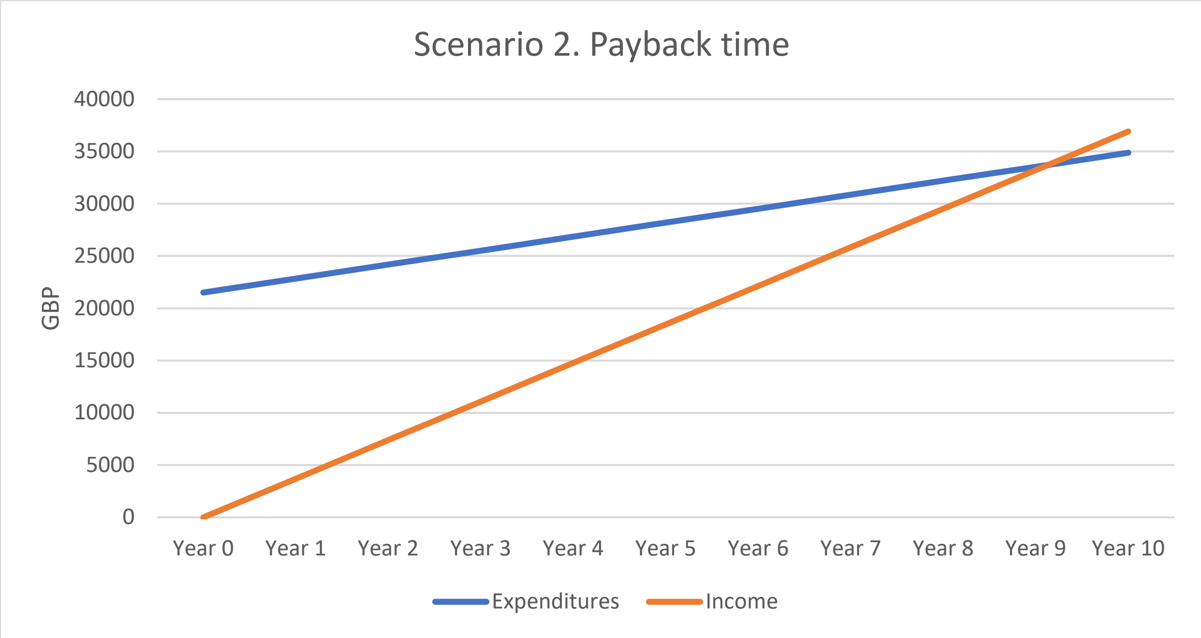

Figure 30 Scenario 2. Payback time.

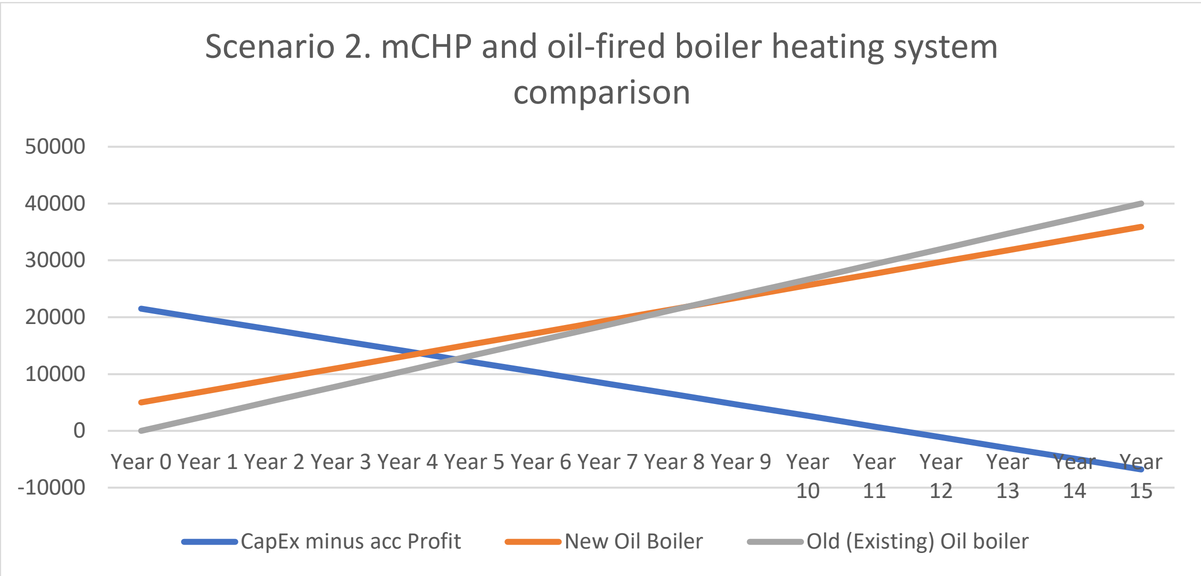

Figure 31 Scenario 2. micro CHP and oil-fired boiler heating systems comparison

Comparison of the micro CHP and oil-fired boiler heating systems in this case is similar to the Scenario 1.

6.5 Scenario 3 Analysis

Installation of a high capacity electrical energy storage and solar photovoltaic system will increase the initial cost of the system by 45% from £20,000 to £29,000. Nevertheless, the payback time of the system will be 7.3 years and is the shortest considering all scenarios. The ROI rate for this scenario will be 13.67%.

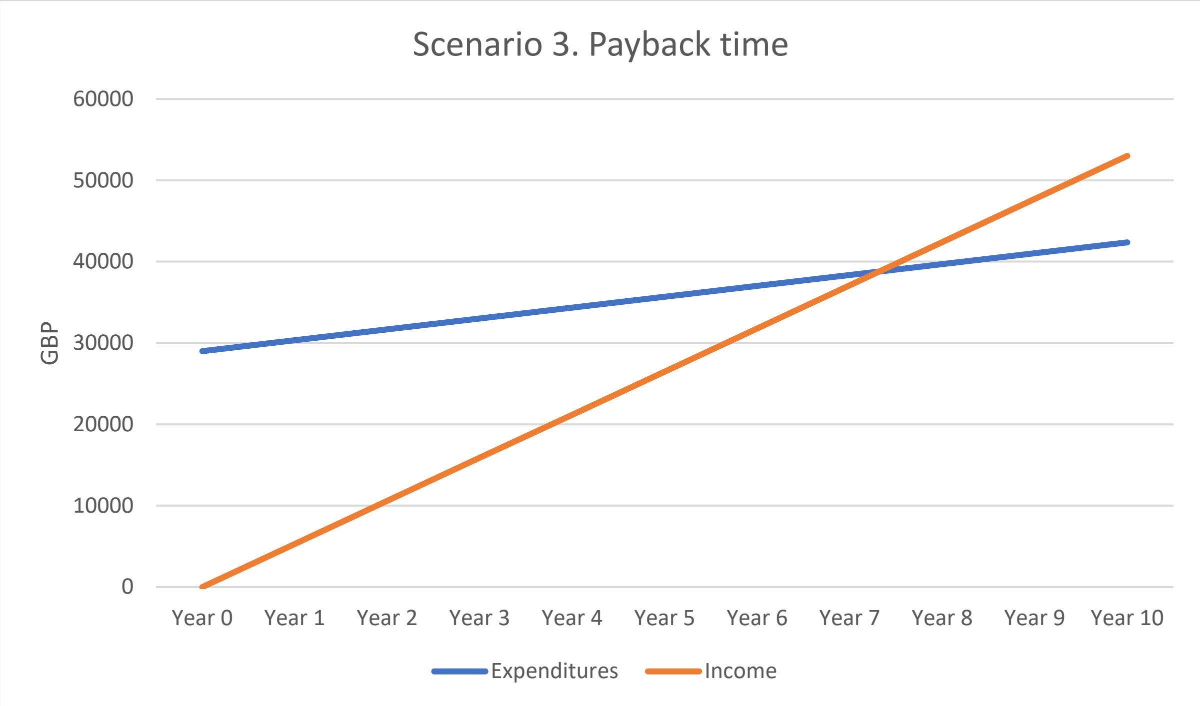

Figure 32 Scenario 3. Payback time

Comparison of the combined micro CHP/Solar PV system and existing oil-fired boiler heating system confirmed that despite the higher capital expenditure, the benefits associated with a higher rate of the electrical energy generation will make the micro CHP system more favourable (in comparison to the oil-fired boiler heating system.)

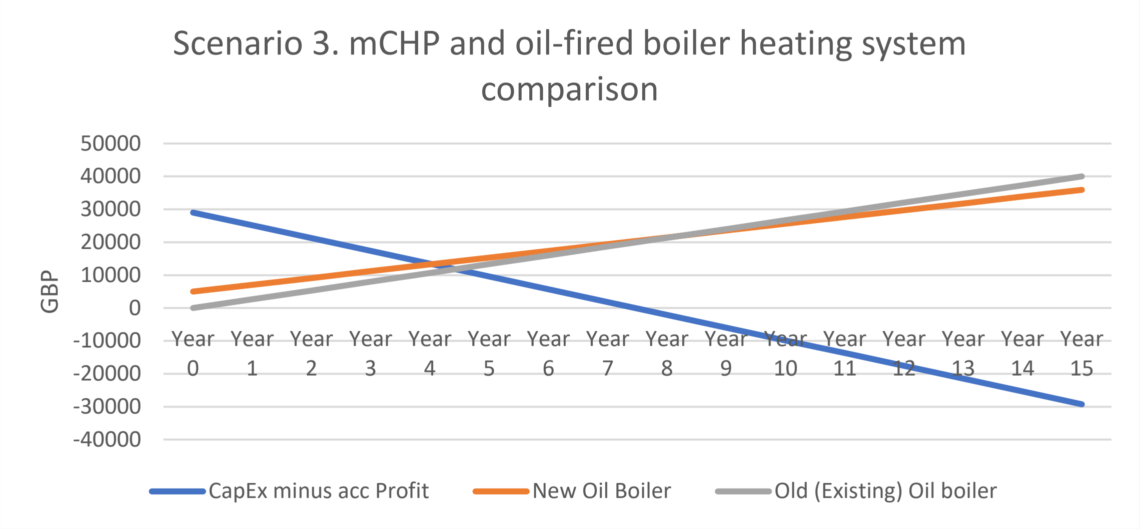

Figure 33 Scenario 3. micro CHP and oil-fired boiler heating system comparison

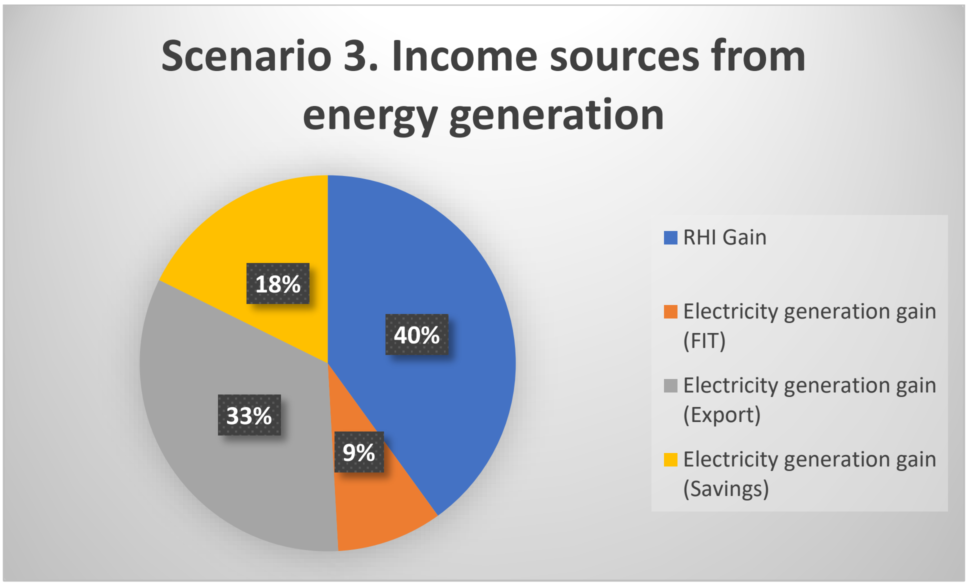

Figure 34 Scenario 3. Income sources from energy generation

7. Environmental Impact

The UK government conversion factors for greenhouse gases were used for greenhouse emission equivalent calculations.

Department for Business, Energy & Industrial Strategy | Department for Environment Food & Rural Affairs

Burning Oil	0.24659	kgCO2e
Biomass (Wood Pellets)	0.0127	kgCO2e
Electricity MIX	0.35156	kgCO2e

Figure 35 Greenhouse gas emission

The main environmental impact of heating systems is the emission of CO_2. When burning oil, CO_2 emissions are approximately 37% greater than those from burning natural gas to give an equal amount of heat, and approximately 13% higher than those from LPG (liquefied petroleum gas). (EST, 2008)

A combined heat and power system is an alternative that may have a lower environmental impact, especially when burning biomass fuels. Also, a micro CHP system generates electricity as a by-product which offsets the carbon weight of central generation.

The government's Standard Assessment Procedure (SAP) is used to calculate the energy and environmental performance ratings and carbon emissions of individual dwellings. To comply with building regulations, a new dwelling must have carbon emissions that do not exceed a target value. Compliance is established by calculating a Dwelling Emission Rate (DER) and Target Emission Rate (TER) (Building Regulations, 2010 and EPBD, 2010)

An Important input (variable) for the accurate energy performance comparison is an energy generating system efficiency. Since the primary energy is heat, the boiler efficiency is an essential factor in the overall efficiency of a domestic central heating system. The UK building regulations set minimum standards of efficiency for most boiler types. These regulations require a higher performance than the EU Boiler Efficiency Directive; however best practice requires installation of boilers of even higher efficiency to be selected (EST, 2008).

Advances in CHP technology mean that when older boilers are replaced, substantial efficiency improvements, and therefore cost savings, can be expected from new equipment.

According to the building regulations newly installed oil-fired boilers should be condensing, with a SEDBUK (Seasonal Efficiency of a Domestic Boiler in the UK) or Energy Related Product directive efficiency of 86% or more (EST, 2008). The efficiencies of the older oil-fired boilers installed before 2008 can be as low as 60%.

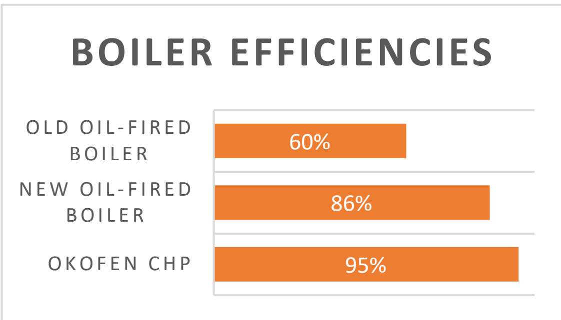

Figure 36 Boiler Efficiencies

According to the data from the simulation, the proposed biomass micro-CHP system will offset as much as 96.55% of greenhouse emissions compared to the existing oil-fired boiler. Having the average efficiency of 60% the oil-fired boiler annual fuel input was identified to be 3261 Litres. When burning this amount of fuel, about 8041.3 kgCO_2 are emitted into the atmosphere. Whereas, the total CO2 emissions for the biomass micro-CHP system will be 277.39 kgCO2 only.

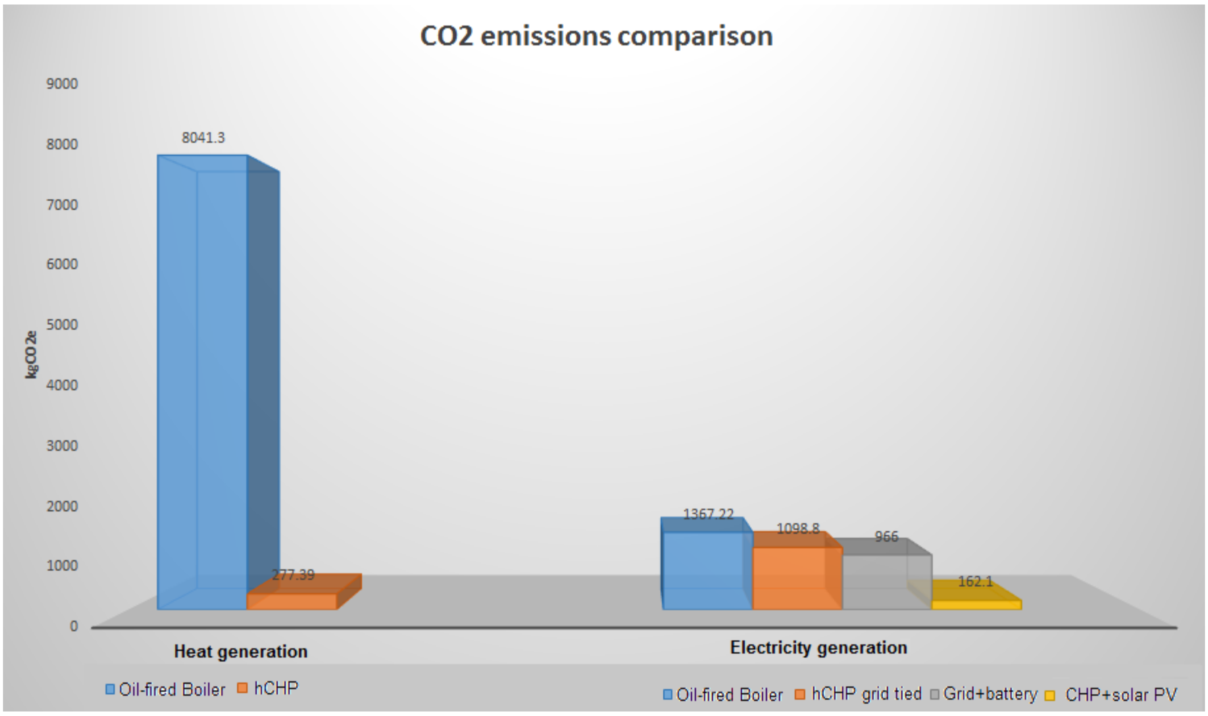

Figure 37 CO2 emissions comparison

In addition to greenhouse emissions due to a heat generation, emissions due to electrical energy generation should be included. The amount of electricity import will differ depends on the simulation scenario. The maximum emission of 1367.22 kgCO_2 will be if 100% of the electrical energy is supplied from the grid. The CO_2 emission will be lower by 29.35% for the battery-assisted system and can be further reduced by 88.12% if the solar PV system is utilised (0kgCO_2e for the off-grid system).

8. Recommendations

It is recommended that adopters of a micro CHP system consider:

Increasing the number of solar panels and/or electrical storage capacity.
This solution will require a total of 60 panels or 44 panels and 2 Tesla Powerwall energy storage units to be installed in order to provide fully grid independent system. Additional benefits can be received from the electrical energy export to the grid, however capital costs will be increased significantly.

Install micro-scale vertical axis wind turbine.
2kW wind turbine will provide enough energy during the winter months (which are usually windier) to cover the energy deficit. The vertical axis wind turbine is chosen as it is more suitable for residential areas where the wind is more turbulent and planning permission of placing a new device is an issue.

Run the CHP system for extended periods from September to January
The increased fuel bill will be covered by the RHI tariff and by the electrical energy savings. This solution doesn't require additional capital expenditures.

Increase the Stirling Engine power output to 1.4kW and electricity-to-heat ratio to 1:6.
According to the simulation model, the engine with power output of 1400 Watts will be able to cover the electrical energy requirements for a single household and will bring additional benefits due to a Microgeneration scheme FIT and electricity export.

9. List of Symbols and Abbreviations

AC	Alternating Current
CaPex	Capital Expenditures
CCGT	Combined Cycle Gas Turbine
CHP	Combined Heat and Power
DC	Direct Current
EES	Electrical Energy Storage
FIT	Feed-in-Tariff
IC	Internal Combustion
ICE	Internal Combustion Engine
LPG	Liquefied Petroleum Gas
micro CHP	Micro Combined Heat and Power
OFGEM	Office for Gas and Electricity Markets
OpEx	Operational Expenditures
PV	Photovoltaic
RHI	Renewable Heat Incentive
ROI	Return on Investments
SE	Stirling Engine
TES	Thermal Energy Storage

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