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MicroCHP or Heat Pump: The question for the most efficient heating solution for domestic buildings through an Economic and Environmental criterion

Relatore: Prof.ssa Anna Stoppato

Correlatore: Dott.ssa Elizabeth Massey (IERC)

Laureando: Giovanni Conti

Matricola:1082722

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Abstract

Heat pumps and microCHP devices are two technologies that can be used in the heating residential context and can help to reduce dramatically the CO_2 emissions from this sector. Moreover, even if they have a high investment cost respect to conventional heating systems, they could lead to a significate savings on utility bills for end-users.

Heat pumps and microCHP are two very different technologies and as such it can be difficult to distinguish a set of criteria on which to assess in absolute values which has the ‘best’ performance. The main aim of this thesis work consists of developing an analysis of performance through a larger perspective that includes economic and environmental criteria in order to assess which is the most efficient appliance in heating a typical Irish house.

This study has been carried out firstly by modelling the building through SketchUp software. Subsequently, after the selection of climate data for 2014, year chosen for the simulation, building thermal and architectural features and the heating plant layout it possible to make the simulation run using EnergyPlus software. In particular, the building is a typical Irish detached house, located in Dublin, comprising 13 rooms and an attic. A hydronic radiant heating system embedded in the building floor heat each room exclusive of the attic. Furthermore, a hot water tank located in the utility room provides domestic hot water required by the tenants. According to the results from the simulation, the nominal heating power output of the system that must supply the thermal demand of the building is 15 kW_{th}. For the simulation, an air-source heat pump and an internal combustion engine microCHP, taken from the default software library, have been selected. From simulation results, electricity profiles of these two appliances have been evaluated in two different weeks: one in January and one in July. According to these profiles, it is possible to observe when there is a thermal demand or when there is an electrical demand by tenants. In order to develop the environmental criterion, it has been necessary to obtain values of Irish grid CO_2 intensity for 2014. Conversely, for economic criterion was fundamental to gather gas and electricity prices, respectively to feed microCHP and heat pump, related to the global annual consumption of the building since, in Ireland, prices are divided in bands depending on different consumption ranges. Moreover, the price of electricity produced by the microCHP device and exported to the grid has been considered.

Environmental analysis results showed that in the year heat pump produces 8536 kg of CO_2 while the microCHP produces 9254 kg. From economic investigation, it is possible to observe that the heat pump has an operation cost that is amount to 3156 € while for the microCHP is 2942 €. Furthermore, a Net Present Cost (NPC) analysis was set up in order to compare these two devices with a conventional boiler used for residential heating. The analysis was developed for a period of 20 years, with a discount rate of 5% and an annual rate of increase of energy price of 1%. Considering an investment cost of 1903 € for a boiler, 4048 € for the heat pump and 13000 € for the microCHP, NPC analysis provides values of 45221.74 € for the boiler, 44441.64 € for the heat pump and 50228.16 € for the microCHP.

The thesis provides an overview of the state of art of these two technologies, with a discussion of various typologies, characteristic parameters and typical values of them. Also presented is a general review on business models suitable for both heat pumps and microCHP devices and the regulatory framework currently adopted in Europe and Ireland. These two aspects are important due to the fact that they could foster the penetration of these technologies in the residential market, helping consumers to overcome typical barriers that are mainly related to social and economic issues.

Sommario

Le pompe di calore e i dispositivi di micro cogenerazione sono due tra le tecnologie utilizzabili nel riscaldamento domestico che possono permettere di ottenere un sostanziale abbattimento delle emissioni di CO_2 in quel settore. Oltretutto, nonostante un elevato costo di investimento rispetto alle tecnologie di riscaldamento convenzionali, possono permettere un concreto risparmio sul costo della bolletta energetica per il consumatore finale. Tuttavia è difficile definire un criterio che stabilisca quale tra le due tecnologie sia la migliore, in termini di efficienza e di performance, dal momento che i parametri utilizzati per caratterizzarle sono diversi.

Per questo, l'obiettivo principale del presente lavoro di tesi è stato quello di sviluppare un'analisi secondo un criterio economico-ambientale che possa valutare quale delle due applicazioni sia la migliore, sotto questi punti di vista, nel riscaldamento di un'abitazione in Irlanda. L'analisi è stata condotta andando dapprima a modellare l'edificio tramite il software SketchUp e, successivamente, procedendo con le simulazioni tramite il software EnergyPlus. Quest'ultimo, in particolare, richiede la compilazione di svariati campi nel proprio interfaccia, che rappresentano i parametri necessari ad effettuare la simulazione. Tra questi si possono annoverare i principali che sono: i dati climatici relativi al luogo e al periodo in cui si realizza la simulazione, le caratteristiche strutturali dell'edificio e il layout dell'impianto di riscaldamento. Specificatamente, l'edificio consiste in una tipica villetta irlandese, situata a Dublino e l'anno scelto per la simulazione è il 2014. La villetta si compone di 13 stanze riscaldate tramite riscaldamento a pavimento ed un attico non riscaldato, non sono presenti le bocchette per il recupero dell'aria esausta se non nella cucina e nei bagni e la casa è ventilata naturalmente tramite l'apertura di porte e finestre. Inoltre, nel ripostiglio è ubicato il serbatoio che contiene l'acqua necessaria a soddisfare le richieste di acqua calda sanitaria dell'utenza. Stando ai risultati ottenuti dalla simulazione, la potenza nominale dell'impianto che deve soddisfare la richiesta termica dell'edificio è di 15 kW_t. Per la simulazione sono stati scelti una pompa di calore aria-acqua con COP di 3.9 e potenza termica di 14500 W ed un dispositivo micro cogenerativo funzionante tramite un motore a combustione interna alimentato a gas con potenza elettrica di 7500 W ed un rapporto di 2.44 tra output termico ed elettrico. Entrambe queste apparecchiature sono state selezionate dalla libreria fornita da EnergyPlus.

Per prima cosa, dai dati sui consumi elettrici annui della pompa di calore e dall'energia elettrica netta (quindi prodotta o importata dalla rete a seconda della situazione) del microCHP, è stato

possibile sviluppare una serie di diagrammi in cui si illustrano i profili elettrici delle due tecnologie in una settimana di gennaio ed in una di luglio. Mettendo a confronto i diversi profili è possibile interpretare in quali occasioni l'utenza ha una richiesta termica o elettrica. Nel primo caso, ad un picco del profilo elettrico della pompa di calore corrisponde un picco negativo dell'impianto cogenerativo il quale esprime che l'elettricità prodotta dal sistema viene esportata alla rete. Nel secondo caso, che si concretizza in estate quando non c'è riscaldamento della casa e il dispositivo cogenerativo è attivo solo per produrre acqua calda sanitaria, ad una richiesta elettrica da parte dell'utenza quest'ultimo deve far fronte importando l'elettricità dalla rete poiché non l'ha prodotta per proprio conto non dovendo fronteggiare alcuna richiesta termica. Successivamente, per ricavare i risultati dell'analisi ambientale si è dovuto ottenere il valore di intensità di CO_2 della rete elettrica nazionale irlandese nel 2014. Per quanto riguarda invece l'analisi economica, dai dati di letteratura si sono desunti i valori del prezzo dell'elettricità e del gas richiesto per alimentare rispettivamente la pompa di calore e il microCHP, sulla base della richiesta globale annua dell'edificio. In Irlanda, infatti, i prezzi di gas ed elettricità sono differenziati in bande a seconda del consumo totale annuo. Inoltre per l'impianto micro cogenerativo si è trovato l'attuale prezzo dell'energia elettrica da esso prodotta ed esportata nella rete elettrica nazionale. Dai risultati dell'analisi si evince che la pompa di calore produce in un anno circa 8536 kg di anidride carbonica mentre il microCHP ne produce 9254 kg. Per quanto riguarda invece lo studio economico, si è trovato che la pompa ha un costo operativo annuo di 3156 € mentre il costo del microCHP ammonta a 2942 €.

A questi risultati si è aggiunta un'analisi comparativa delle due tecnologie rispetto ad un boiler a gas convenzionale secondo il criterio del Valore Attuale Netto (VAN) considerando un arco temporale di 20 anni e valutando solamente i flussi di cassa uscenti e quindi le spese sostenute per garantire il funzionamento dei tre sistemi. In questa ricerca, si è assunto un tasso di sconto pari al 5% ed un valore di incremento annuo del prezzo dell'energia pari all'1%. Considerando un costo di investimento pari a 1093 € per il boiler, 4048 € per la pompa di calore e 13000 € per il microCHP, lo studio consegna un VAN pari a 45221.74 € per il boiler, 44441.64 € per la pompa di calore e 50228.16 € per il microCHP. Queste analisi forniscono dei risultati che danno la possibilità di evidenziare quale delle due tecnologie possa essere la migliore, e sotto quale punto di vista, nel riscaldamento di un edificio residenziale.

Oltre a ciò, obiettivi secondari del lavoro di tesi sono stati quello di fornire una panoramica sullo stato dell'arte delle due tecnologie andando ad esporre le principali tipologie di pompe di calore e microCHP (utilizzate anche in settori diversi da quello residenziale), i parametri che ne definiscono le prestazioni e i loro valori caratteristici. Questo excursus ha avuto come obiettivo principale quello di chiarire come i parametri distintivi di questi due sistemi non siano confrontabili tra loro e divenga quindi necessario sviluppare altri criteri per poter avere una comparazione tra di essi. Inoltre, il lavoro di ricerca bibliografica ha interessato anche gli aspetti del business model e del quadro normativo relativi a queste due apparecchiature. In particolare, per quanto riguarda il business model si sono definiti quali possono essere i modelli principali adattabili a queste situazioni (soprattutto ESCO e leasing), mentre per quanto concerne il quadro normativo si sono fornite le direttive principali che regolano il settore a livello europeo ed irlandese. Questi due aspetti rappresentano un importante aiuto alla possibilità di diffusione all’interno del mercato del riscaldamento residenziale per le pompe di calore e i microCHP, dal momento che possono aiutare i potenziali consumatori finali a decidere di installarli superando le principali barriere che sono soprattutto di natura economica (elevato costo dell’investimento iniziale e lunghi tempi di ritorno), sociale (scarsa conoscenza della tecnologia e dei suoi benefici) e politica (mancanza di una normativa stabile e trasparente in molti paesi europei, Irlanda compresa).

Table of contents

Chapter 1: Introduction

1.1 Background

The residential sector accounted for just over a quarter (27%) of all primary energy used in Ireland in 2013 and it was the second largest energy using sector, after the transport sector. It was also responsible for 27% (10.5 million tonnes) of energy related CO_2 emissions in 2013 (Dennehy & Howley, 2013). Energy use in the sector includes energy for heating, hot water, cooking, cleaning, washing, drying, lighting, cooling and entertainment. Space heating and hot water provision account for the majority of fuel use in the residential sector (Gaffney & Clancy, 2015). The principal sources of energy supply to the sector are oil, electricity and natural gas, respectively accounting for 36%, 25% and 20% of energy use in 2013 (Dennehy & Howley, 2013). In the five year period from 2006 to 2013, overall residential sector energy consumption fell by 4.4% (0.9% per annum) while, in the same period, residential sector CO_2 emissions fell by 11% (2.3% per annum) significantly faster than the fall in energy consumption (SEAI, 2012) (SEAI, 2011). On a weather corrected basis, the “average”[1] dwelling in Ireland consumed almost 20,000 kWh of energy in 2013. This comprised approximately 5,000 kWh of electricity and almost 15,000 kWh of non-electrical consumption. Moreover, the average dwelling was responsible for emitting 6.4 tonnes of energy-related CO_2 emissions in 2013; of this 3.9 tonnes of CO_2 (61%) came from direct fuel use and the remaining 2.5 tonnes arose indirectly from electricity use (SEAI).
The average energy efficiency in Irish housing improved by 34% over the period 1997 to 2013 (2.5% per annum) and the total energy spend in the sector during 2013 was 3 € billion, an increase of 10% on 2006 (Dennehy & Howley, 2013).

In the recent past, most Irish houses were heated by open fires with back boilers, oil/gas based central heating systems, or electrical storage heaters (SEAI, 2014).
Today, home heating costs are one of the greatest budgetary concerns for any Irish household. In recent years, motivated by rising energy costs and the impacts of new legislation for the

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[1] Total residential energy divided by the number of permanently occupied dwellings.

built environment Irish homeowners understand better that energy needed for heating homes and buildings can be reduced through reducing heat loss and improving the building fabric. For this reason, heat pump and microCHP devices are proving an attractive alternative for the replacement of conventional gas central heating boilers when they reach the end of their useful life. In particular, these two technologies could offer lower operating costs and reduction of carbon emissions (Energy Saving Trust, 2001) (SEAI, 2014).

In order to inform policy formulation the SEAI (Sustainable Energy Authority of Ireland) Energy Modelling Group produced forecasts which examine energy usage out to 2020 (Dennehy & Howley, 2013). The so-called NEEAP/NREAP forecast assumes that the 20% energy efficiency improvement by 2020 and 16% overall RES (Renewable Energy Systems) target, required by the EU Renewable Energy Directive (based on achievement of the 40% renewable electricity, 12% renewable heat and 10% renewable transport targets), are achieved. An overall decrease in residential energy demand to 2020 is forecast (16%). With the exception of renewables demand for all other energy sources is expected to fall and the same tendency will be observed for electricity too. The greatest decrease is expected for coal at approximately 7% per annum, followed by natural gas at 3% per annum and oil at between 2% and 3% per annum. Oil will still have the highest share in final residential energy consumption in 2020 but electricity will overtake natural gas to have the second largest share in the sector (Dennehy & Howley, 2013) (European Commision , 2012). Figure 1.1 shows the NEEAP/NREAP forecast for the residential sector.

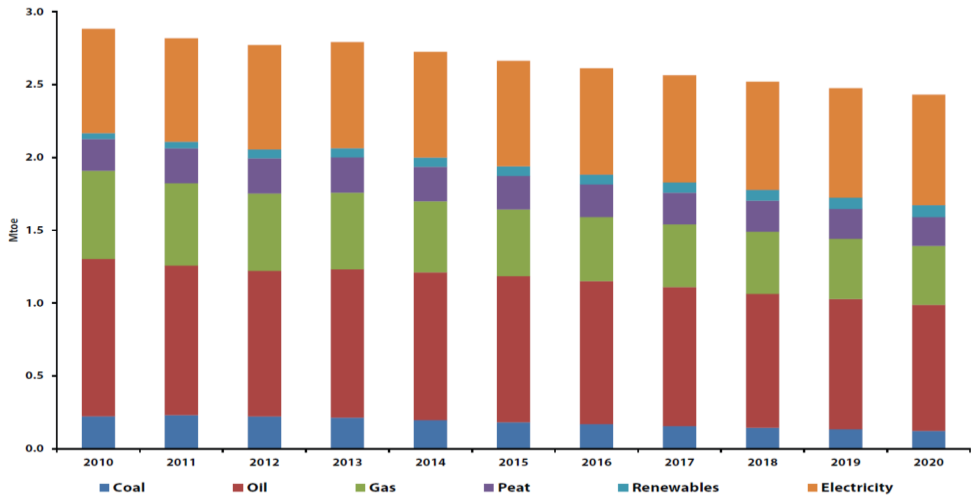

Figure 1.1. Residential final energy demand by fuel 2010 to 2020 (NEEAP/NREAP Scenario). Source: SEAI.

Under the Energy Efficiency Directive 2012/27/EC[2] and the Renewable Energy Directive 2009/28/EC[3] EU Member States are encouraged to lower energy consumption and are legally bound to increase the deployment of renewable energy technologies. Ireland must increase renewable energy use to 16% of gross final energy consumption by 2020 and have committed to reducing the national energy demand by 20% compared to the average 2001-2005 level through energy efficiency measures by 2020 (Department of Communications , 2014). Energy efficiency policies have been successful in reducing household demand for thermal energy, while building regulations for household dwellings implemented in 2008 have led to an increased amount of renewable energy being used for heat (SEAI, 2014). In spite of these developments, fossil fuels continue to dominate heat production in the residential sector; the higher capital costs of new technologies such as heat pumps and microCHP, access to the natural gas grid and a lack of market experience in the use of these options have all added to the list of barriers restricting the uptake of alternatives (Irish Academy of Engineers, 2013) (Hewitt, 2012).

Due to their potential for high efficiencies, heat pumps are considered a renewable source of heat under EU Renewable Energy Directive 2009/28/EC[3]. In addition, heat pumps can provide an alternative to the existing heat sources used to meet the nation’s thermal energy needs. The potential benefits may include:

- Lowering national reliance on imported fossil fuels;
- Reducing CO_2 emissions;
- Delivering renewable heat;
- Operating in conjunction with smart grid technology to maximise the benefits from renewable electricity generation.

The European Union CHP Directive[4], approved in February 2004, sought to create a favourable environment for CHP installations. The directive contained definitions for micro, small and large scale CHP. In table 1.1 it is possible to observe the operational capacity in 2014 for microCHP (Holland, Howley, & Dineen, 2015).

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[2] European Union, ‘Energy Efficiency Directive 2012/27/EC’, Brussels, 2012.

[3] European Union, ‘Renewable Energy Directive 2009/28/EC’, Brussels, 2009.

[4] European Union, ‘Directive 2004/8/EC on the promotion of cogeneration based on useful heat demand in the internal energy market’, 2004.

Table 1.1. Number of units and installed capacity for microCHP in 2014 in Ireland.

Electrical capacity size range	**Number of units**	**Number of units (%) (compared to other sizes)**	**Operational capacity (MWe)**	**Operational capacity (%)**
MicroCHP < 50 kWe	69	26.3	0.5	0.2

For microCHP technology benefits may incorporate (Cogen Europe):

- Empowering energy consumers;
- Producing heat and power at point of demand and at time of maximum demand;
- Balancing renewables;
- Saving primary energy;
- Decarbonising heat and electricity production.

Policy intervention to overcome the barriers to energy technology uptake in the heat sector has proven more difficult than in other areas. The heat sector, in Ireland as in Europe, has seen much less activity to support new technologies (such as heat pump and microCHP) when compared with other sectors (European Commision, EACI, 2011). This brings to the fragmented nature of the heat market, the difficult of retrofitting buildings with new heat technology and the administrative difficulties of implementing policy support for renewable heat (Clancy, 2015).

The generation and use of heat energy is shaped by the complexity in the interactions among generation, supply and end-use arising from the physical characteristics of heat energy. Heat energy is difficult to transport over significant distance in an efficient way and this means that the economies of scale that are available in electricity sector are unavailable. As a result, heat is generally not traded as a commodity and typically does not have a market price (Clancy, 2015). Space and water heating in homes typically occurs over the winter months, with a residual demand for water heating over the summer months. This reduces the relative importance of fuel consumption and ongoing maintenance costs, and increases the relative importance of upfront installation costs in heat technology choice. The available technology choice is more diverse due to the lower temperature requirements of space and water heating. Moreover, tenants and landlords may have different incentives, with landlords' choice of heat technology dependent mainly on the installation cost, while tenants are more concerned with the ongoing running costs. This can result in a technology with a higher overall lifetime cost being chosen (Howarth & Sanstad). Additionally, the suitability of a building for a technology type, and consumers attitudes towards changing technology, are also important determinants of which technology is chosen when replacing and old gas or oil central heating system.

Nevertheless, both heat pumps and microCHP could represent a natural evolution of existing boiler technology. For instance, many of components in a microCHP unit are the same as, or based on, those found in a traditional gas boiler. The similarity of microCHP to the gas boiler means consumers and businesses also have a familiarity with them (Cogen Europe). In the same way, for heat pump system design and installation are crucial and it has to be designed to integrate with other systems in the dwelling (SEAI, 2013).
In general, for both technologies before the installation, some features have to be analysed:

- Available budget: focus should be on reducing the heat demand of a building through low/medium/high cost impact measures, for example improving the insulation, air tightness and glazing upgrade.
- Space available on site: especially for heat pumps that are not always feasible due to the space needed for the collector;
- Dwelling suitability: examination of the energy performance of the residential building and assurance that existing heat distribution system can be used in conjunction with a heat pump or microCHP device;
- Heat requirement: establish annual consumption;
- Data availability: fuel cost comparison calculators and got quotes from suppliers;
- Simple payback: calculation of how many years' savings will be equivalent to the overall cost of the system.

1.2 General overview

The general aim of this research work is to analyse the different performances between an air-source heat pump and an internal combustion engine microCHP into heating a typical Irish residential building. The comparison between these two technologies is carried out through different criteria that study energy, economic and environmental performances. Alongside with this main purpose, there is also the objective to provide a brief overview about the current state of art of the heat pump and microCHP appliances and the present situation for business models available in order to foster the market penetration of these technologies. The methodology used in this project for reaching those objectives includes:

- Literature review of the state-of-the art technologies for heat pumps and microCHP heating processes for residential buildings;
- Review of feasible and appropriate business models;
- Brief review of relevant European and Irish policies and regulations;
- Assessment of energy performance through the investigation of electricity profile of two devices;
- Evaluation of CO_2 yearly emissions and total annual costs for both technologies in order to determine which option may be more attractive;
- Net Present Cost (NPC) assessment in order to compare these two appliances with a conventional heating boiler.

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Chapter 2: Literature review

2.1 Overview of space heating technologies for residential buildings

The aim of this paragraph is to provide a general overview of the state-of-art of the current heat pump and micro cogeneration technologies used for residential buildings; the analysis intention is to understand the main parameters that can define these two technologies and current values that could be reached nowadays.

2.1.1 Heat pumps

A heat pump is a device that is able to transfer heat from one fluid at a lower temperature to another at a higher temperature (Robur, 2016). The transfer of thermal energy from a heat source to a heat sink is made through a compression cycle that takes advantage of temperature gradients (European Commision, 2014).

Pumps can be driven by electricity or by thermal energy, the main difference being the electrical heat pumps use a mechanical compressor, while thermally activated heat pumps achieve compression by thermal means.

One of the advantage of using thermally activated heat pumps is their high output temperature and simple integration with existing heating systems and infrastructure. Conversely, electric heat pumps can operate on the grid in response to electricity prices and contribute to optimal load management (The European Technology Platform on Renewable Heating and Cooling, 2016).

The most common heat pumps in the residential sector are air/air units and split-air conditioners for air conditioning. ASHPs (Air Source Heat Pumps) can provide sanitary hot water and space heating, while avoiding the need for expensive ground or water loops. GSHPs (Ground Source Heat Pumps), which use underground heat exchangers, have higher efficiencies in cold water than ASHPs (Sustainable Energy Ireland, 2009).

In order to have a general overview about which are the main parameters and values that define the performances of heat pumps it is possible to follow an analysis carried out by the Energy Saving Trust.

This organization monitored a large number of heat pumps in residential properties across UK and Ireland from April 2009 to March 2010 (Energy Saving Trust, 2013).

This project was developed by the Energy Saving Trust and delivered from a wide range of stakeholders including main UK's energy suppliers and heat pump manufactures and installers including: Danfoss UK, NIBE, Mitsubishi Electric, Worcester Bosch and Baxi Group.

The sample included a large number of site permutations and included the following installation types:

- Air source and ground source heat pumps;
- Heat pumps installed in private and social housing properties;
- Heat pumps installed in new build and retrofit properties;
- Heat pumps providing heating only;
- Heat pumps providing heating and hot water;
- Heat pumps installed with different heat delivery systems: under-floor heating and/or radiators.

The electricity consumption includes the energy input to the compressor and controls, plus either the circulating pumps for the ground coil in the case of ground-source heat pumps.

The specification required other measurements to be taken to determinate the overall performance of the heat pump. These factors can both influence performance, provide data and may include:

- Heat source temperatures;
- Heat sink temperature, including central heating flow and return temperature and temperature of domestic hot water;
- Room temperature;
- Outdoor ambient temperatures.

In the case of ground-source heat pumps, the heat source temperatures required are:

- The ground temperature at a distance from the heat extraction point;
- The ground temperature close to the ground point;
- Flow and return temperatures on the heat source loops.

For air-source heat pumps, just the air inlet temperature is required.

Efficiency of a heat pump may be defined as the ratio of heat output to the electricity used. This ratio is dependent on (amongst other things) the temperature of the source (air or ground), the flow temperature of the heat provided and the range of electricity inputs included in the system boundary. There is difference between various definitions of efficiency (coefficient of performance, seasonal coefficient of performance, seasonal performance factor and system efficiency) and the range of different system boundaries that can be used (Energy Saving Trust, 2012).

First, the *coefficient of performance (COP)* is determined by laboratory testing at defined source and heat flow temperatures; the temperature at which COP is measured must always be quoted (CEN/TC 228, 2011). The COP is the quotient of the current heat output power and the current electricity power input (Kadar, 2012). This value is normally between 3 and 4 in an average application (e.g. air/water pump). An example of that can be observed in Table 2.1 where both flow temperature and ambient temperature are reported.

Table 2.1. Specified COP values at different ambient and central heating flow temperatures for a typical air-source heat pump.

Source: Energy Saving Trust

Ambient temperature (°C)	**Central heating flow temperature (°C)**		
	35	**45**	**55**
-15		2.2	
-7		2.65	
2	3.84	3.28	
7	4.39	3.69	3.19

Secondly, the *seasonal coefficient of performance (SCOP)* is a modelled estimate of the efficiency of a heat pump in a given climate and it is based on laboratory measurements of coefficient of performance, combined with climate data for a given location.

Then the seasonal performance factor (SPF) is the measured annual efficiency of a heat pump at a particular location. It is important to define the difference between SPF from the boundaries that could be taken i.e. SPF_{H1}, SPF_{H2}, SPF_{H3} and SPF_{H4} (Nordman, Andersson, Monica, & Markus, 2010). The four seasonal performance factors are illustrated in the Figure 2.1.

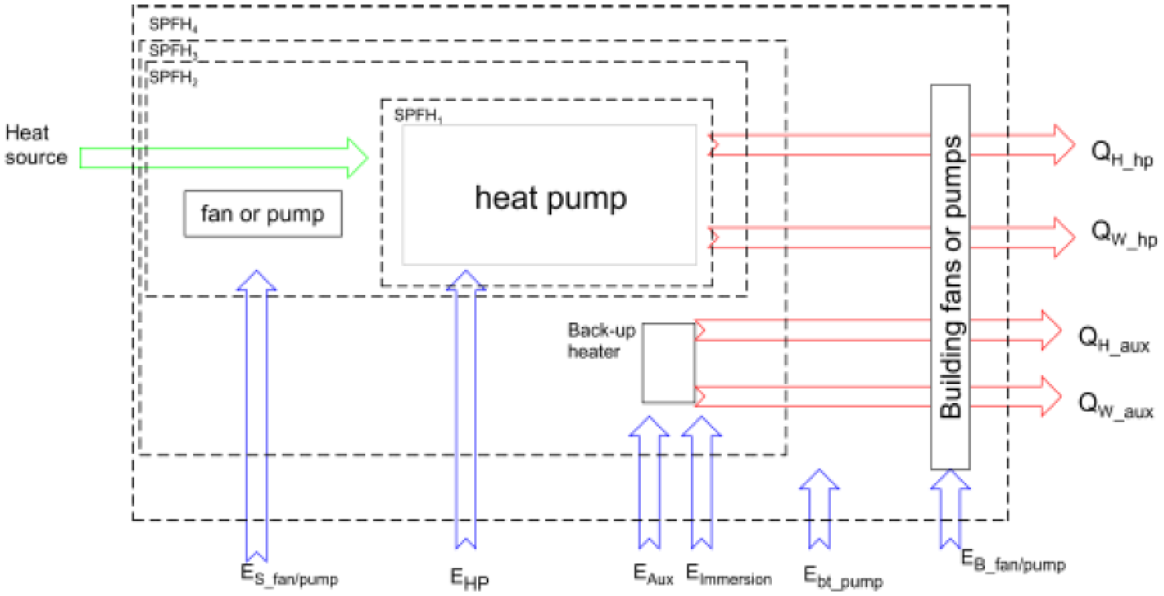

Figure 2.1. System boundaries for space and water heating circuits.

Source: Energy Trust Saving

Since in the trial just SPFH2 and SPFH4 are used to evaluate system efficiency is given the definition of them:

- SPFH2: the system boundary consists of the heat pump unit and the equipment to make the source energy available for the heat pump and this parameter evaluates the performance of heat pump operation. SPFH2 takes into account, in addition to SPFH1, total source fan consumption, and the sink fan consumption only for non-ducted internal units (SEPEMO, 2011).

$$SPF_{H2} = \frac{(Q_{H\_hp} + Q_{W\_hp})}{(E_{S\_fan/pump} + E_{HP})}$$

- SPFH4: consists of the heat pump unit, the pumps or fans to make the source energy available, the auxiliary electric heater and domestic hot water immersion and all auxiliary pumps including those on the heat sink. SPFH4 is equal to SPFH3 for non-ducted unit (SEPEMO, 2011).

$$SPF_{H4} = \frac{(Q_{H\_hp} + Q_{W\_hp} + Q_{H\_aux} + Q_{W\_aux})}{(E_{S\_fan/pump} + E_{HP} + E_{Aux} + E_{Immersion} + E_{bt\_pump} + E_{B\_fan/pump})}$$

Designations of electricity inputs and heat outputs for the definitions of seasonal performance factors are presented in Table 2.2.

Table 2.2. Designation of electricity inputs and heat for definition of seasonal performance factors.
Source: Energy Saving Trust

Quantity		**Explanation**
Heat	*QH_hp*	Space heating provided by the heat pump
	QW_hp	Water heating provided by the heat pump to the domestic hot water cylinder
	QH_aux	Space heating, provided by the auxiliary electric heater
	QW_aux	Water heating, provided by the electric immersion to the domestic hot water cylinder
Electricity	*ES_fan/pump*	Electricity used by the source pump (for ground-source) or fan (for air-source)
	EHP	Electricity used by heat pump (excluding the ground loop/air inlet and auxiliary heating/immersion)
	Eimmersion	Electricity used to supplement domestic hot water production
	EAux	Electricity used to supplement space heating
	Ebt_pump	Electricity used by buffer tank pump (if present)
	EB_fan/pump	Electricity used by the fan or pump of the central heating system

Following the analysis accomplished by Carbon Saving Trust, we have to say that different typologies of heat pumps have been studied before (*phase I*) and after (*phase II*) some modifications of the system that were different for each situation. In particular, one of the aim of the research was to understand performances of devices studied in order to see how modifications could have improved them, paying particular attention to the factors that influence system performances.

In phase I 83 properties were monitored by the Energy Saving Trust. 38 of these systems were selected for interventions and further analysis and the selection process was determined by:

- Identification of the need for an intervention or interventions;

- Willingness of the manufacturer to carry out the interventions;
- Willingness of the householder to participate in a further year of monitoring.

A further six sites were added to the sample. Therefore, for phase II 44 sites were analysed (Energy Saving Trust, 2013). The most common system configuration was a ground-source heat pump, supplying radiators and domestic hot water (21 cases), followed by an air-source heat pump supplying radiators and domestic hot water (12 cases) (Energy Saving Trust, 2013).

Between phase I and phase II a wide range of interventions were made. These have been classified as major, medium and minor:

- Major interventions (such as replacement of the heat pump, reduction of area heated by heat pump, recharging refrigerant or repair leak to ground loop) required input from a heat pump expert;
- Medium interventions (e.g. installation of a buffer tank or new hot water tank, new radiators or circulation pumps, connection of shower to heat pump circuit, etc.) could be carried out by a plumber;
- Minor interventions (such disabling auxiliary heater or extra insulation) consisted of changes to controls or a general service.

From this path, it is possible to obtain typical values of system efficiency and seasonal performance factors for ASHPs and GSHPs studied.

It is important to notice that the ambient temperature influences the system efficiency so, in order to compare system efficiencies from phase I and phase II, the data have corrected for the effect of ambient temperature (Energy Saving Trust, 2012).

2.1.1.1 Ground source heat pumps

For phase I of the analysis the average efficiency of this kind of heat pump got by the trial is 2.39, with a range of 1.55-3.37. As reported in Table 2.3 and Table 2.4 we can report the system efficiency of heat pumps as a function of emitter type. Largely under-floor, which includes systems with under-floor heating only, under-floor heating and domestic hot water, and under-floor heating and radiators; or largely radiators, which includes systems with radiators only and systems with radiators that also provide hot water (Energy Saving Trust, 2013).

Table 2.3. System efficiency of ground-source heat pumps as a function of heating type.
Source: Energy Saving Trust

System efficiency	**Largely radiator heating**	**Largely under-floor heating**
Number	27	22
Average	2.23	2.58
Range	1.8-3.0	1.6-3.4

Table 2.4. System efficiency of ground-source heat pumps as a function of hot water production.
Source: Energy Saving Trust

System efficiency	**With hot water production**	**Without hot water production**
Number	42	7
Average	2.34	2.68
Range	1.6-3.4	1.8-3.4

In the phase II, after modifications for each sites, it is possible to calculate SPFH2, SPFH4 and system efficiency for the heat pumps in the trial. It was not possible to calculate all of these quantities in every case due to metering arrangements or heat meter faults (Energy Saving Trust, 2013). For example, SPFH2 can only be calculated for 36 of the 44 systems examined in the trial (Energy Saving Trust, 2013). Values are reported in Table 2.5.

Table 2.5 SPFH2, SPFH4 and system efficiencies for phase II.
Source: Energy Saving Trust

	SPFH2	**SPFH4**	**System efficiency**
Number	21	21	26
Average	3.08	2.82	2.54
Range	2.2-3.9	2.0-3.9	1.5-3.3

2.1.1.2 Air source heat pumps

Concerned to air source heat pumps, the average efficiency for the phase I is 1.82, with a range between 1.2 and 2.2 that is less compared to ground source type. There is no apparent trend in these data since there are only 17 systems with radiators and 5 with under-floor heating. Therefore, it is not possible to determinate reliable statistics for the system performance (Energy Saving Trust, 2013). This situation is explained in Table 2.6 and Table 2.7.

Table 2.6. System efficiency of air source heat pumps as a function of heating type.
Source: Energy Saving Trust

System efficiency	Largely radiator heating	Largely under-floor heating
Number	17	5
Average	1.82	1.86
Range	1.2-2.2	1.4-2.2

Table 2.7. System efficiency of air source heat pumps as a function of hot water production.
Source: Energy Saving Trust

System efficiency	With hot water production	Without hot water production
Number	13	9
Average	1.83	1.83
Range	1.4-2.2	1.2-2.2

These values are lower compared with the same showed for ground source heat pumps. Also for air source heat pumps for phase II, after modifications, it is possible to obtain a table as for the other typology as represent in Table 2.8.

Table 2.8. SPF_{H2}, SPF_{H4} and system efficiencies for phase II.
Source: Carbon Saving Trust

	SPF_{H2}	SPF_{H4}	System Efficiency
Number	15	15	16

Average	2.72	2.45	2.16
Range	2.2-3.9	2.0-3.7	1.7-2.7

In the trial, six of the 44 heat pumps supplied only space heating while remaining 38 supplied both space and water heating. In 11 cases, the complexity of the systems or faults with heat meters meant that it was not possible to produce separate estimates of space and water heating efficiencies (Energy Saving Trust, 2013).

In the whole analysis space heating efficiencies, as SPFH2, can be estimated for 34 sites. For example, we could see the situation for space heating efficiencies, as SPFH2, for both typologies as reported in Table 2.9.

Table 2.9. Space heating efficiencies for air- and ground-source heat pumps (as SPFH2).
Source: Carbon Saving Trust

	SPFH2	
	Air source	**Ground source**
Number	14	20
Average	2,73	3,21
Range	2,2-3,2	2,2-4,6

On average, the ground-source heat pumps showed higher space heating efficiencies (as measured by SPFH2). Space heating efficiencies is a function of heating delivering during the heating season. There could be a slight drop off in efficiency of ground-source heat pumps at low annual heat demands (below 5000 kWh) while the efficiency stabilises at higher levels of heat delivery (Zotti & Nordman, 2012).

A similar evaluation could be done to evaluate the space heating efficiency (as SPFH2) for both typologies as shown in Table 2.10.

Table 2.10: Water heating efficiencies for air- and ground-source heat pumps (as SPFH2).
Source: Carbon Saving Trust

	SPFH2	
	Air source	**Ground source**
Number	11	16
Average	2,34	2,35
Range	1,8-3,2	1,6-3,6

The efficiency of water heating is strongly influenced by the temperature at which domestic hot water is stored. The efficiency of water heating (as SPF_{H2}) is a function of the average temperature of the domestic hot water tank. In particular, we can expect the highest water efficiencies in sites where domestic hot water tank has a very low temperature (30-40 degrees) (Charlick & Summerfield, 2013).

2.1.1.3 Conclusions about air source and ground source heat pumps

To sum up, some considerations could be made:

- Space heating efficiencies are greater for the ground source heat pumps than for the air source heat pumps (average SPF_{H2} of 3.21 against 2.73);
- On average, water heating efficiencies are lower than space heating efficiencies (2.35 for both air and ground source, measured with SPF_{H2});
- For some individual sites, water heating efficiencies may be higher than annual space heating efficiencies since the amount of energy used for water heater is roughly constant in the year, but space heating load increases with ambient temperature, while space heating efficiency decreases with ambient temperature.

As already said, SPF_{H4} takes account of all electricity used by heating system and therefore is the most appropriate measure of efficiency for householders to understand the costs and benefits of a heat pump (Miara, 2007). According to Energy Saving Trust trial's results was possible to calculate SPF_{H4} for 15 air source and 22 ground source systems. The average SPF_{H4} values were found to be **2.45 ± 0.11** for air source and **2.82 ± 0.10 for** ground source (Energy Saving Trust, 2013).

Several case studies generally indicate good performance as measured by SPF_{H2}, with mean values being **2.68** for air source heat pumps and **3.10** for ground source heat pumps (Baylon, Strand, Davis, Robison, & Kruse, 2005).

From trial's results, for 34 cases (14 air source and 20 ground source) it was possible to calculate SPF_{H2} for space heating and the average space heating efficiencies, as SPF_{H2}, were found to be **2.73** for the air source and **3.21** for ground source heat pumps (Energy Saving Trust, 2013).

Finally, in 27 cases it was possible to calculate SPF_{H2} for water heating that was found to be **2.35** with no detectable differences between air and ground source heat pumps (Energy Saving Trust, 2013).

2.1.1.4 Absorption heat pumps

Gas absorption heat pumps could be fired by natural or propane gas, they do not use any refrigerants harmful to the environment and they are easy to install. Like the electric heat pumps they use renewable energy (air, ground, water) and they can supply hot water for heating in winter (Critoph, 2013).

The main differences with electric heat pumps are the use of a gas burned instead of an electric compressor and the use of a water-ammonia solution instead of a refrigerant.

Another important thing to notice is that the primary energy source of this type of heat pumps are rated differently than electric heating equipment since they use gas. Gas absorption heat pumps efficiencies are rated with GUE (Gas Utilization Efficiency).

The field trial followed for electrically driven heat pumps did not consider on its analysis absorption heat pumps. Therefore, it is possible to consult manufacturers' web sites in order to obtain some features that can define this typology of heat pumps.

According to Robur Corporation technical data it is possible to see that at nominal conditions the heat energy of the unit's absorption cycle combined with the heat extracted from the outdoor air is approximately 126%.

Considering GAHP-A model, an air to water gas fired absorption heat pump with several applications into residential sector, some features are available (Robur S.p.A., 2013):

- Domestic hot water delivered at 65°C with net GUE of 1.24;
- 38 kW supplied to radiators at 50°C with net GUE of 1.38;
- Efficiency over 129%, recovering 38% of renewable energy from air and saving up to 40% in operational costs compared to a condensing boiler;
- Reduction the need of electric power by approximately 87% in comparison with electrical compressor units.

2.1.2 MicroCHP

Combined heat and power (CHP), or cogeneration, is the simultaneous production of useful heat and electricity from a single source, close to the point of use (BDR Thermea, 2015). MicroCHP refers to small-scale production of heat and power for individual commercial buildings, apartments and individual homes. In particular, micro cogeneration unit shall mean a cogeneration unit with a maximum capacity below 50 kWel (European Commision, 2004). As in a conventional boiler, the heat is used for space heating and hot water, but unlike in a conventional boiler, electricity produced can be used on site or exported to the national grid. The electricity generated in this way leads to significant carbon savings and an important determinant of the effectiveness of microCHP is the carbon intensity of the national electricity supply. In countries where most electricity is derived from gas or coal, considerable carbon savings arise (Sustainable Energy Authority of Ireland, 2011).

The efficiency of energy conversion to useful heat and power is potentially greater than by using the traditional alternatives like boilers or conventional fossil fuels fired central electricity generation systems. If managed properly this increased efficiency can result in lower costs and a reduction in greenhouse gas emissions (Knight & Ugusal, 2005). In addition, cogeneration has the advantage of diversifying electrical energy production, thus potentially improving security of energy supply in the event of problems occurring with the main electricity grid (Harrison & Redford, 2001).

With the ability to attain overall efficiencies above 90%, microCHP units meet the demand for heating, space heating and hot water in buildings, while providing electricity to replace or supplement the grid supply.

To have an overall view about the state or art of this technology it is possible to refer to a field trial that the Sustainable Energy Authority of Ireland (SEAI) commissioned in 2009 to assess the operation, performances and benefits of microCHP in residential and commercial situations.

Thirteen sites were selected across Ireland and included both existing buildings and new build developments; for each site measurements were made of the gas and the electricity consumed and of the electricity generated and the heat produced (both for space heating and for hot water) (Sustainable Energy Authority of Ireland, 2011).

Data were collected from thirteen residential and commercial sites in Ireland, analysed in terms of operation, performance, efficiency and potential energy and carbon savings. All microCHP devices considered in the trial are internal combustion engines fed by natural gas. According to field trial's results engines operated between 70-90%, with majority 80-85% and an average of 82% overall efficiency (Sustainable Energy Authority of Ireland, 2011). The overall efficiency includes both electrical import and export, and thus accounts for the efficiency of the engine while in standby mode as well as during periods of operation. The amount of time an engine is in standby has a direct effect on the annual efficiency of the appliance due to the electricity consumed during these periods. In particular, an engine that only operates for limited periods is in standby for considerable time and will have a reduced efficiency compared with a similar engine that operates for long period (Cogen Europe).

For thermal efficiency, that shows little seasonal variation, engines operate between 50-60%, with majority between 55-60% and an average of 58% (Sustainable Energy Authority of Ireland, 2011).

Concerning on electrical efficiency the range is between 20-30%, with majority between 20-25% and an average of 24% (Sustainable Energy Authority of Ireland, 2011).

Thermal efficiency varies more than electrical efficiency, although the changes are not significant. Electrical efficiency, however, remains almost constant and the difference is accounted for by variations in fuel supply, operating conditions and demand (Sustainable Energy Authority of Ireland, 2011).

Overall, thermal and electrical efficiencies are calculated as follows:

- $\text{Overall efficiency} = \dfrac{\text{Heat + Electricity Generated}}{\text{Gas and Electricity Consumed}}$;
- $\text{Thermal efficiency} = \dfrac{\text{Heat Generated}}{\text{Gas and Electricity Consumed}}$;
- $\text{Electrical efficiency} = \dfrac{\text{Electricity Generated}}{\text{Gas and Electricity Consumed}}$.

Moreover, in the analysis a carbon benefit ratio (CBR) assessment was carried out for each site. This is one way to measure the reduction of carbon emissions by offsetting the electricity consumed from the grid. This parameter depends on:

- The carbon content on the fuel it uses to generate heat and power (although this doesn’t vary much);
- The carbon content of the grid supplied electricity that microCHP displace (this vary a lot between countries).

Carbon benefit ratio is calculated as follows:

$$CBR\% = \frac{(Heat\ Output * CEF_{gas} + Electricity\ Generated * CEF_{electricity})}{(Gas\ Used * CEF_{gas} + Electricity\ Used * CEF_{electricity})} * 100$$

where:

- Heat output = Total heat output from microCHP appliance
- Electricity generated = Gross electricity generated from the microCHP
- Gas used = Total gas used by the microCHP
- Electricity used = Total electricity used by the system (pump, fans, controls, etc.)
- CEF_{gas} = Carbon emission factor for gas ($kgCO_2/kWh$)
- $CEF_{electricity}$ = Carbon emission factor for electricity (kgCO2/kWh)

For Ireland it is possible to assume a value of CEF_{gas} of 0.205 kg/kWh and for $CEF_{electricity}$ of 0.511 kg/kWh (SEAI, 2014).

According to the trial, all sites were shown to be saving carbon, with CBR values of over 115%, with majority operating between 120-130%. This means all sites are benefiting from the microCHP appliances in terms of carbon emissions. Engines with the longest operational hours displayed the highest efficiency and carbon savings (Sustainable Energy Authority of Ireland, 2011).

The CBR does not take into consideration the efficiencies of alternative heat sources, such as boilers. It is rather an absolute measure of carbon benefit that can be applied to any technology (ene.field, 2014)

Another important parameter for defining microCHP devices is primary energy savings (PES) that is a measure of the energy savings provided by cogeneration. It is calculated as follows in accordance with the EU Cogeneration Directive[5]:

$$PES = 1 - \frac{1}{\frac{CHPH\eta}{refH\eta} + \frac{CHPE\eta}{refE\eta}}$$

(Sustainable Energy Authority of Ireland, 2011).

where:

- $CHPH\eta$ is the heat efficiency of the cogeneration product defined as annual useful heat output divided by the fuel input used to produce the sum of useful heat and electricity from cogeneration;
- $refH\eta$ is the efficiency reference value for separate heat production;
- $CHPE\eta$ is the electrical efficiency of the cogeneration production defined as annual electricity from cogeneration divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration;
- $refE\eta$ is the efficiency reference value for separate electricity production.

The majority of sites have a primary energy saving of between 15% and 25%. This means that, although each site uses more fuel to generate its own electricity, the larger reduction in energy use in central power generation leads to net savings of 15% to 25%. As with efficiency and CBR, PES are proportional to the length of time the engine is operational (Sustainable Energy Authority of Ireland, 2011).

Another field trial that could be followed to get results of typical parameters of microCHP devices is one carried out by Carbon Trust's MicroCHP Accelerator between 2008 and 2010. This was the first large-scale independent field trial of microCHP systems in domestic and small commercial applications implemented in UK (Carbon Trust, 2011). 87 microCHP systems, including 72 domestic Stirling engines and 15 internal combustion engine systems, were installed and monitored in typical UK households and small commercial applications (Carbon Trust, 2011). In particular, the domestic microCHP systems considered in the field

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[5] Directive 2004/8/EC of the European Parliament and of the Council of 21st December 2006 on established harmonised efficiency reference values for separate production of electricity and heat.

trial were all based on Stirling engines, installed as main heating system, providing both space heating and domestic hot water to a single household; typically they have peak thermal outputs in the range of 8-15 kW and peak electrical outputs in the range of 1-3 kW.
We can see which are the models featured in the field trial in the Table 2.11

Table 2.11. Domestic microCHP models featured in the field trial
Source: Carbon Trust

Manufacturer	**Model**	**Technology**
Whispergen	Mk4	Stirling engine
Whispergen	Mk5	Stirling engine
Microgen	Microgen	Stirling engine
Disenco	Home Power Plant	Stirling engine
Baxi Innotech	Home Heat Centre	PEM fuel cell

According to field trial’s results, the mean measured annual thermal efficiency was 71%, the mean electrical efficiency was around 6% while the overall efficiency was 96%. Then, the carbon benefit ratio of the electricity generated by the domestic microCHP systems was 88% (Carbon Trust, 2011).
Due to electricity consumed in start-up and shut-down, the analysis showed that current Stirling engine microCHP units typically need to operate for a minimum cycle length of over one hour to provide an overall carbon saving benefits. Therefore, performances would be expected to be poor for systems installed in households with relatively low heat demands and for all systems during summertime (Carbon Trust, 2011).

After that, it is possible to analyse the differences among technologies that run microCHP devices. These five main categories are:

- Stirling engines;
- Internal combustion engines;
- Fuel cells;
- Organic Rankine cycles;
- Gas turbines.

With the exception of fuel cells, all of them use an engine as a generator and thus produce electricity.

2.1.2.1 Stirling engines

Stirling engines are external combustion engines used in a much smaller proportion of microCHP units, although they are gaining in popularity. They are currently being launched into the domestic market as a replacement for gas boilers (Sustainable Energy Authority of Ireland, 2011).

In theory, these engines are very efficiency; in practice on the market, they have an electrical efficiency of about 10%. Moreover, they have small sizes and limited range of outputs that make them less attractive in the commercial market (Department of Energy & Climate Change, 2008).

Overall, the domestic Stirling engines microCHP systems achieved a carbon saving of around 5%, although the performances in individual households varied considerably. The Stirling engines microCHP systems performed better in households with higher heat demands (typically larger detached houses with four or more bedrooms).

Some features, taken from different manufacturers, are shown in Table 2.12.

Table 2.12. Features of Stirling engines microCHP systems.
Sources: Different companies' web sites

Manufacturer	Applications	Electrical Output	Thermal Output	Cost	Features
Whispergen	(Mk4, Mk5) Individual family home	1 kWe	7 kWt	€ 14000 (installed cost)	Availability in Germany since 2010
Baxi Ecogen	Individual family home	1 kWe	3-24 kWt	£ 6-8000 (installed cost)	Availability in UK since 2010
Vaillant	(Eco Power 1.0) Single family home	1 kWe (Electrical efficiency 26.3%)	2.5 kWt	/	Overall efficiency 92%

Infinia	(STC) Individual family home	1 kWe	4-40 kWt	£ 6-8000 (supply cost only, 2010)	Limited availability, 2012
Disenco	(Inspirit) Homes	0.5-3 kWe	4-40 kWt	/	/

2.1.2.2 Internal combustion engines

The internal combustion engine microCHP are based on the automotive engine and are the most established of all microCHP appliances. The majority of these engines could be modified to improve their longevity (Sustainable Energy Authority of Ireland, 2011).

To maximise economic benefits, residential and small commercial scale microCHP should operate for over 3000 hours/year. They have been used primarily in the commercial sector (with 20-25% average electrical efficiency) and designs that are more modern can vary their output, based on the demand for heat and/or electricity.

These products are also suited for family homes with electrical output around 1 kWe and thermal output around 3 kWt; generally they work with electrical efficiency around 25% and have lower heat output compared with Stirling engines (Sustainable Energy Authority of Ireland, 2011).

Different characteristics of these microCHP systems are shown in Table 2.13.

Table 2.13. Features of internal engines microCHP systems.
Sources: Different companies' web sites

Manufacturer	Applications	Electrical Output	Thermal Output	Cost	Features
Honda	(Ecowill) Individual family homes	1.2 kWe	3 kWt	£ 5600 (installed cost)	Overall efficiency 85% Available in Japan since 2003
Vaillant	(EcoPOWER 1.0)	1 kWe	2.5 kWt	€ 23000 (installed cost)	Overall efficiency 92%

	Individual family homes (indoor installation)	(Electrical efficiency 26%)		€ 16000 (product only)	Available in Japan since 2011
Proenvis	(Pri 5.2) Individual family homes	1.3-2 kWe (Electrical efficiency 25%)	3-5.5 kWt (Thermal efficiency 68%)	/	Overall efficiency 93% Available in Germany since 2013
Kirsch	(Nano) Large family homes or small apartment blocks	1.9 kWe (Electrical efficiency 19%)	9 kWt (Thermal efficiency 76%)	€ 10900 (supply only)	Available in Germany since 2012

2.1.2.3 Fuel cells

Fuel cells operate on principles similar to those of a battery. Electrochemical cells consume fuels to produce a small DC voltage. These cells are arranged in series and the DC voltage is converted into an AC voltage (Fuel Cell Today, 2012).

Fuel cells are promising in the microCHP field due to their potential for high electricity output and net electrical production that is higher than Stirling and internal combustion engines.

Current prototypes designs are complex require careful control at start-up and tend to be large, but future models are expected to be smaller.

This typology of microCHP system is widely spread in Japan; the Japanese Government has supported the commercialization of fuel cells in residential heat and power through the ENE-FARM scheme (Energy Farm). The major regional companies who also maintain the fuel infrastructures distribute ENE-FARM fuel cells (Fuel Cell Today, 2012).

It is possible to report some features, taken from manufacturers' web sites, of PEMFC[6] and SOFC[7] technologies as reported in Table 2.14 and Table 2.15. A few companies have launched products down-rated from 1 kWe to around 700 We to minimise the export.

Table 2.14. Features of fuel cells microCHP systems (PEMFC typology).
Sources: Different companies' web sites

Manufacturer	Electrical Output	Thermal Output	Cost	Features
Toshiba	700 We (Electrical efficiency 35%)	/	$ 20000	Equipped with a supplementary heater to provide operational flexibility Available in Japan since 2009
Baxi Innotech	1 kWe (Electrical efficiency 32%)	1.7-20 kWt	/	Field trial in Germany and UK
Elcore	300 We (Electrical efficiency 33%)	600 Wt (Thermal efficiency 65%)	€ 9000 (installed cost)	First field trial installation in 2013
Viessman	750 We (Electrical efficiency 37%)	1 kWt+ 19 kWt with boiler (Thermal efficiency 53%)	€ 36000 (including installation)	Available in Germany since 2014
Panasonic	700 We (Electrical efficiency > 40%)	940 Wt	€ 25000	Available in Japan since 2011, in Europe since 2014

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[6] PEMFC (Proton Exchange Membrane Fuel Cell).
7 SOFC (Solid Oxid Fuel Cell).

JX Eneos	700 We (Electrical efficiency 40%)	/	$ 31000	Available in Japan since 2011

SOFC technology was largely considered as unsuitable for microCHP due to its relative inflexibility to modulate power output and limitations in thermal cycling. However, the high potential efficiency, the ability to reform fuel and other technical features may eventually make this technology the leading for microCHP (Fuel Cell Today, 2012). Some technical features are reported in table 2.15.

Table 2.15. Features of fuel cells microCHP systems (SOFC typology).
Sources: Different companies' web sites

Manufacturer	**Electrical Output**	**Thermal Output**	**Cost**	**Features**
Ceramic Fuel Cells (Bluegen)	1.5 kWe (Electrical effiency 60%)	600 Wt (Thermal efficiency 25%)	€ 25000	Bluegen 1.5 kWe available in UK and Germany
Acumentrics	250 W- 10 kW (Electrical efficiency increases with nominal capacity improvement)	/	/	Overall efficiency 90% with heat recovery Available since 2013
JX Eneos	700 We (Electrical efficiency 45%)	/	$ 31000 (retail)	Available in Japan since 2012

2.1.2.4 Organic Rankine cycles

An organic Rankine cycle (ORC) microCHP uses a working fluid that is first pumped through a boiler, then evaporated and passed through a turbine and finally condensed. The fluid is organic and usually have a lower boiling point than that of water (Sustainable Energy Authority of Ireland, 2011).

Some ORC engines are quite small and light, with theoretical net electrical efficiency up to 17% and some units can vary their output in response of the heating demand (Zywica, Kicinski, & Ihnatowicz, 2015).

There are several large biomass machines installed in continental Europe but in practise this technology is still at the field trial stage for domestic applications.

Overall, typical applications are:

- Low enthalpy geothermal plants;
- CHP biomass powered plants, in the range between 400 and 1500 kWe;
- Heat recovery applications, in the range from 400 to 1500 kWe;
- Solar applications.

2.1.2.5 Gas turbines

A gas turbine microCHP unit works by mixing air and gas in the combustion chamber and igniting it. There are many theoretical advantages to gas turbine used for microCHP like high efficiency, clean combustion and low maintenance but despite these advantages, they are still more expensive than internal combustion engines (Sustainable Energy Authority of Ireland, 2011). This is due to the few moving parts, lower operation and maintenance that make them comparable with internal combustion engines.

However, they are more widespread than Stirling and internal combustion engines in the market.

2.2 Business models for residential space heating

While there is a great deal of literature on the subject of business models for distributed energy technologies (Boehnke J. W., 2007), some common terms have been established and alternative models are beginning to emerge (The MIT Energy Initiative, 2013), (Parker, 2015). . Using a definition from one of the foremost experts in distributed energy technologies business models, ‘A business model could be defined as a strategy to invest in a particular technology which creates value and leads to an increased penetration of this technology in the built environment. Therefore, it is a description of a planned or existing business that includes information on value creation and market orientation' (Würtenberger, 2012).

The importance of business models as topics for innovation have been increasing with the advent of e-commerce since due to the need for new strategic analysis tools that provide firms with a mechanism to prove how they create value and how they compete in the market. The internet has been a disruptive force that completely changed the way traditional business was conducted and created new opportunities for value proposition, revenue models and configurations (Boehnke, 2007). For example, a successful business model can show how financing and implementation of certain technologies in buildings are organised such that barriers for deployment can be overcame.

Business models describe the structure and strategy behind a business case. Structural components such as value proposition, key activities, cost structures and revenue streams are important operational focus areas of a business. The strategic parameters of a business model captures the logic and reasoning for initiating an activity i.e. an investment in the built environment due changes in the market. The reasoning may also include a financial calculation to show the profitability of the planned investment.

2.2.1 Components of business models

The market components of a business model define how a company delivers value. Four main components can be distinguished i.e. *value proposition*, *strategy*, *customers* and *revenue model* (Boehnke, 2007).

The *value proposition* shows the benefits that a business model creates for stakeholders and eventually the final customer.

The *strategy component* describes the ability of a business to compete, relative to the value proposition and to transformational strategies directed towards changing the market environment.

The *customer base* must be understood since it is essential to be aware of target groups in order to prepare a coherent value proposition.

Finally, the *revenue model* describes how the value delivered to the market is translated into sale revenues and profits (Boehnke, 2007), (Berthold Hannes, 2013).

It is important that all components of a business model fits together. For example, the strategy, the customer base and the revenue model must be logically related to the value proposition. Moreover, value partners and the value creation architecture must be fit for purpose and in-line with the company's strategic resources. Finally, great reciprocity is between the market and the configuration components reflected in the design of a business model. Hence, we should expect to see businesses with well-designed business models secure a commensurate place in the market.

2.2.2 Business models situation for microCHP devices in residential buildings

Residential microCHP energy markets play a key role for increasing liberalisation and for fundamental changes through developments such as the trend towards decentralisation. In particular, residential microCHP has the potential to be disruptive for existing energy supply systems and to impact market dynamics. One of the most interesting components of a microCHP business model is the value proposition for consumers to change their energy supply to microCHP since it gives them a way to save money on their energy bills (Boehnke, 2007). Strategically, the microCHP since business model can complete in the market as a low cost solution either in comparison to other micro cogeneration products or in comparison to other options for supplying residential buildings (Boehnke, 2007).

In accordance with value proposition and strategy, microCHP business models must identify the right customers for their products that could be both final consumers and partners. Specifically for three groups of customers: those that actively look for environmental benefits (eco-active), customers that view environmental benefits as an additional aspect of product quality (eco-rational) and finally those that do not give additional value to the environmental benefits (eco-passive) (Ecuity Consulting LLP, 2013), (Environment, 2015).

It is then useful to analyse the market status and the potential to reduce carbon emissions with microCHP installations in appropriate domestic and residential applications. Generating own power with microCHP can also improve power resilience.

In Japan, as in many countries, the power to most residential buildings is supplied from centralized power generation plants over the national electricity grid. The introduction of distributed sustainable energy systems, as recommended for residential buildings and the large-scale adoption of distributed generation units such as microCHP could radically change the electricity system turning consumers into producers. The Japanese government has supported the residential-based ENE-FARM fuel cells microCHP since 2009, providing subsides to reduce the system cost to consumers and after the 2011 earthquake and tsunami there has been a growing interest for producing from renewable energy. In Japan the main technology used for microCHP is the fuel cell and the goal is to install 5.3 million residential ENE-FARM units by 2030 (Curtin, 2013).

In January 2013, the European project Ene.field began with the ambition to be the largest European-based demonstration of fuel cell-based microCHP. This is a five-year project co-funded with the European Commission and 26 partners across the heating and energy industry that will deploy up to 1000 residential fuel cell installation across several countries in this period (Fuel Cells and Hydrogen Joint Undertaking Programme, 2013).

Such as the ENE-FARM program in Japan, the Ene.field program is supported by governments of each country where devices are installed, co-funded by the partners and the European Commission’s Fuel Cells and Hydrogen Joint Undertaking Programme (FCH JU). In both cases, the main objectives of these two projects are to show the market potential, cost and environmental benefits of using microCHP devices in residences and to create a more mature supply chain ready for installations of large number of these appliances. Moreover, especially in Japan, this governmental programme wants to make microCHP technology cost, particularly for fuel cells, more competitive lowering their price through mass-production. This case is a strong example for showing how important government intervention can be to foster the market in order to make distributed energy technologies (such as microCHP) a competitive and attractive solution for consumers.

2.2.2.1 Market players

It is possible to define the main characteristics of the market for the residential microCHP starting with a definition of who are the market players involved in selling and purchasing the products (Boehnke, 2007).

On the supply side market players can be divided into four groups that are:

- *Equipment manufacturers* and *merchants* i.e. companies that produce microCHP;
- *Service providers* that install equipment in consumer homes and by advising residents to use micro cogeneration equipment. Usually service providers are developed by energy supply companies;
- *Providers of infrastructure* in particular fuel suppliers (natural gas mainly) and also electricity network operators;

- *Financers* such as venture capitalist, banks or investment funds that encourage market development by investing in microCHP and by starting their experience and knowledge.

On the demand side market players can be split into:

- *Landlords* that agree to install the microCHP device and usually pay the set-up costs. Moreover for rental residences an incentive to involve occupants in the new decentralized scheme economically may be needed;
- *Occupants* who can be classified such as for landlords, according to the location, age and size of the residence;
- *Creditors* (typically banks) less concerned with the installation of microCHP devices and rather more involved in purchasing decisions.

2.2.2.2 Market drivers and penetration

According to (Boehnke, 2007), market drivers for microCHP in residential buildings can be divided in four categories that are:

- *Structural market drivers* which are related to the situation of energy system and dwellings. Main items of this group that affect diffusion of microCHP devices are energy prices, availability of fuels, design of electricity networks and built environment;
- *Technological market drivers* study suitability of microCHP installations for residential buildings. In this area the crucial entries are performance factors, convenience factors, costs and financing;
- *Social market drivers* associated with people involved in the decision about installing or not the microCHP device. In this case one can analyse features that are related to consumers mind and their behaviour such as opinions about microCHP, education and motivation of consumers;
- *Political market drivers* i.e. the impact that public institutions have on the market for residential microCHP. An example of that was given before analysing differences between Europe and Japan situations. Governmental actions, incentives and regulations could concern structural, technological and social market drivers.

Since political measures influence other market drivers one can see how there are a large number of policies that influence positively market development. Policies supporting microCHP can be targeted directly at particular technologies for residential cogeneration, e.g. internal combustion engine, or for microCHP in general.

2.2.2.3 Market barriers

It is important then to analyse the larger obstacles that can prevent a wider diffusion of microCHP products. Barriers exist with respect to each of the market drivers shown and can be grouped similarly (Boehnke, 2007):

- *Structural market barriers* e.g. low power price and feed-in-tariff schemes not transparent;
- *Technological market barriers* e.g. weak efficiencies under part load or high noise and vibration levels for ICE;
- *Social market barriers* for example insufficient knowledge about microCHP technology;
- *Political market barriers* such as no promotion of residential microCHP and little effort to improve its image and minimal governmental sponsored incentives.

These barriers can be overcome with appropriate policies for each. With regard to market liberalisation, easier network access for microCHP or building regulations that require developers to consider microCHP. For structural barriers, tax incentives or active participation of public institutions in development projects. For technological, social and political barriers financial incentives from the government for both consumers and technologists, institutionalised marketing campaigns or education or education programmes for consumers including community outreach programmes such as the Renewable Energy Hub[8] that connects stakeholders in the sector.

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[8] https://www.renewableenergyhub.co.uk/

2.2.3 Business models situation for heat pumps in residential buildings

The number of heat pump units in the European heat pump market increased by 3% in 2013 and during the last 20 years, the total amount of installed heat pumps has exceeded 6.74 million (EHPA, 2014).

Table 2.16. Heat pumps in Europe sales and stock (2005-2013).
Source: EHPA, 2014

	Sum EU-11	Sum EU-21	Total Stock
2005	446 037		1 015 607
2006	504 428		1 525 401
2007	568 131		2 114 519
2008	770 538		2 918 976
2009	686 076		3 644 998
2010	671 392	800 388	4 437 530
2011	666 873	808 591	5 237 003
2012	621 818	750 436	5 979 042
2013	636 639	769 879	6 741 251

Global heat pump market is driven by growing demand of technology using renewable energy resources and emitting less CO_2 (Future Market Insights, 2015).

Government commissions and programs have activated also for heat pumps in order to foster the development and market adoption of this advanced, energy-efficient technology. In particular, main efforts regarded ground-source and advanced air-source heat pumps.

GSHPs (ground-source heat pumps) technology has gradually improved in last years and has achieved a growing share in heating, cooling and sometimes water heating equipment markets with modest policy strength (Goetzler, 2009).

Historically ASHPs (air-source heat pumps) have been used for heating and cooling in moderate climate but this trend changed in recent years as high natural gas prices and advanced technology that avoids resistance heating during cold weather make this type of heat pumps attractive also for colder climates. Therefore, in the future we can expect to have more air-source heat pumps used in cold climate (Goetzler, 2009).

It is again possible to evaluate the market status of heat pump devices.

The global heat pump market is geographically segmented into seven key regions: North America, South America, Eastern Europe, Western Europe, Asia Pacific, Japan and Middle East & Africa. Europe holds the major share in global heat pump market, followed by North America and Asia Pacific (Future Market Insights, 2015).

GSHPs are a small fraction of the global installed capacity for space-conditioning applications. However, in recent years they have grown dramatically especially in North America and Europe (Lund, 2013).

In Europe, there are several cases where trade associations were formed to promote heat pumps and develop education and training programs in order to achieve the market growth. Two examples of this are the European Heat Pump Association[9] and the Heat Pump Association in the UK[10].

The Asian heat pump market is less established than in Europe and America. However, there has been some recent growth in China and Japan with also activities of research and development (Navigant Consulting, 2009).

This brief introduction shows the uptake of GSHPs and ASHPs in different markets worldwide. A comprehensive analysis of energy-savings potential of this technology is beyond the scope of this work, however, is possible to quickly show that the cost and performance of GSHPs and advanced ASHPs will vary significantly depending on regional construction practices, climate conditions and utility rates.

2.2.3.1 Market players

For the heat pumps, the market players are the same of those shown for the microCHP situation.

2.2.3.2 Market drivers and penetration

It is possible to show the market penetration of GSHPs and advanced ASHPs as a function of an economic parameter, usually the simply payback period. This criterion is used to represent the economic attractiveness of those two types of heat pumps compared to alternative technologies.

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[9] http://www.ehpa.org/

[10] http://www.heatpumps.org.uk/

If payback periods are of five years or longer, the market penetration of a technology will be lower. Usually a five-year payback is considered as threshold for widespread market adoption of a certain technology. Moreover, payback periods of ten years suggest that those applications are limited to niche market (Goetzler, 2009).
As seen for microCHP technology also for heat pumps one can observe how market penetration of these devices depends on many factors that are not accounted for by simply payback period. In particular, for space conditioning equipment these factors include:

- Percent increase in first cost;
- Degree of knowledge of brands that are present in the market;
- Product warranties offered;
- Success of marketing and promotional campaigns or branding;
- Non-energy benefits such as comfort or noise;
- Degree of interruption associated with new installations;
- Desire of having “green image” technology by end-users.

Again, it is possible to confront these aspects with drivers reported for the microCHP and it can be shown that there is similarity between these two technologies concerning market penetration levels.

2.2.3.3 Market barriers

In order to evaluate how advanced ASHPs and GSHPs are diffused into the market the barriers to uptake must be considered:

- Technological barriers such as poor performance or poor reliability mainly due to low manufacturing volumes, immature product design, high refrigerant cost, high cost of materials, etc.;
- Market barriers such as high installation costs result in poor payback, space constraints in many urban area, operating cost dependent upon electricity pride, etc.;
- Lack of awareness by the residents;
- Lack of familiarity that affects cost or discourages potential users;
- Lack of supporting sales, installation and service infrastructure;

- Limited number of qualified, trained installers;
- Restrictions due to environmental regulations.

By analysis, we can see that these barriers are quite similar to those presented for microCHP market; generally, it is possible to observe how it is always a matter of structural, technical, social and political issues.

Both advanced ASHPs and GSHPs show potential for important unit energy savings that returns a deployment of these technologies into the market. However, while GSHPs generally have efficiency advantages, advanced ASHPs tend to be more economical (following the simple payback period results). GSHPs market may expand for many years probably without capture a major area of heat pumps market (Hofmeister, 2014).

In order to foster a penetration in the market of energy efficient heat pumps should be supported with incentives such as federal tax credit or utility rebates based on energy efficiency achievements. In addition, for first-cost reductions for GSHPs one can evaluate potential economies of scale, alternative business models and potential partnering relationships.

Finally, to overcome social barriers there can be some promotional actives such as:

- Support training for designers and installers;
- Consider partnerships to create new business models in order to reduce costs;
- Promote information programs;
- Work together with local governments, utilities, developers, manufacturers and installers to create community-based systems.

2.2.4 Business models applicable for both technologies in residential buildings

Based on the common drivers for value creation, business models for these two technologies in the built environment can be distinguished among:

- *Product Service Systems (PSS)* are business models that make use of the delivery of the function of a product combined with relevant service. ESCOs are the most important examples of the PPS business models in the energy sectors (Würtenberger, 2012). Other contracting forms can also been relevant such as Energy Supply

Contracting (ESC), Energy Performing Contracting (EPC) and the combination of those could be used called Integrated Energy Contracting (IEC) (Hofmeister, 2014). These can be explained as follows:

1. In the ESC typology a contractor implement measures that insures the heat supply and also finance them and it is repaid from the payment for heat;
2. In the EPC model, the contractor implements measures that reduce energy use, finance them and it is repaid from the savings;
3. For the IEC model, there is a combination of supply of useful energy with energy conservation measure in the whole building (Bertoldi, 2013).

- *Leasing* of renewable energy equipment that enables a building owner to use and energy installation without having to buy it;

- *Feed-in remuneration scheme* where the producer of energy receives a direct payment per unit of energy produced.

2.2.4.1 ESCO

There are common features for an ESCO business model suitable for both microCHP and heat pump devices. In general, ESCO’s remuneration is performance based paid on the measured outputs as opposed to the inputs consumed and it guarantees for the result and for all cost of the service package. All ESCO business models lead to a reduction of final energy demand and achieve environmental benefits due to the associated energy and emission savings in addition to non-energetic benefits, e.g. an increase in comfort (Bertoldi, 2013). Typically, an ESCO acts as a general contractor and implements a customized service package (e.g. design, installation, (co-)financing, operation & maintenance, optimization, fuel purchase, user motivation) (Bleyl, 2008).

For implementation, the building owner assigns a customized energy service package and demands guarantees for the results of the measure taken by the ESCO. The necessary components for implementing energy projects are mainly:

- Technology (suppliers, construction, operation & maintenance, etc.);
- Know-how (engineers, architects, consultants, innovation, etc.);

- Energy (gas, fuel oil, etc.);
- Money (capital, banks, subsides, etc.);
- Legislative framework (laws, technical rules, etc.).

It is possible to observe how an ESCO works from the Figure 2.2.

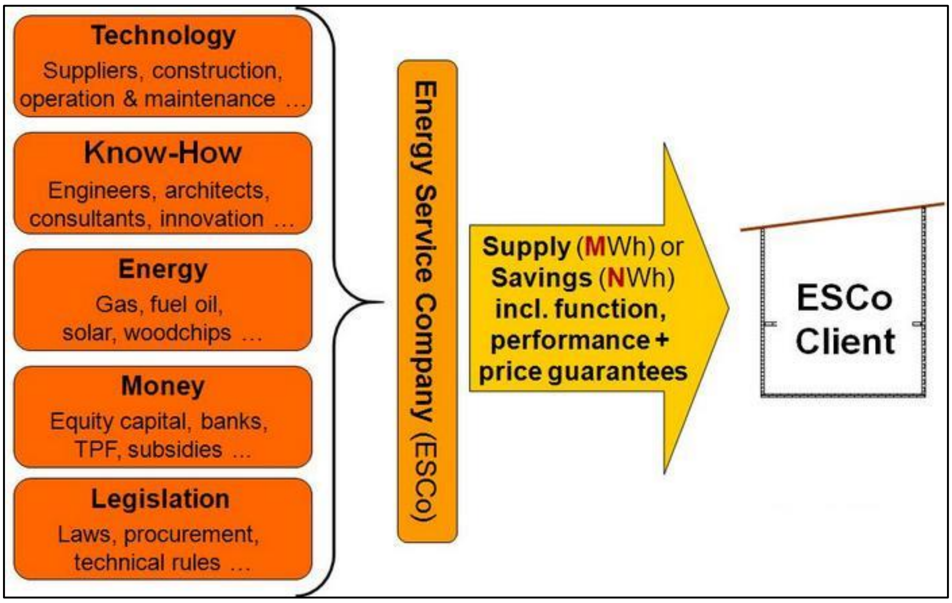

Figure 2.2. Different services of the ESCO.

Source: Bleyl, 2009

Main actors in this business model are ESCO itself and the business owner. Usually outsourcing of up-front costs is often the key driver to engage with the ESCO and it could happen that ESCOs are not able to offer attractive financing conditions in comparison to a building owner, especially when the client is a large organization. Therefore, the ESCO service package does not necessarily need to include financing, it could be provided by the building owner, the ESCO or a third financing partner, depending on who has better access to capital and financing conditions (Würtenberger, 2012).

Combinations of these options are also possible to account for the specific project and actors involved and many times a mixture of these financing sources is often the best choice to balance risks.

2.2.4.2 ESC

In an Energy Supply Contracting (ESC) model, an ESCO supplies energy such as electricity or hot water to a building owner or building user. The ESCO's remuneration is performance based and depends on the useful energy output delivered. This business model gives the building owner the opportunity to outsource technical and commercial risks associated with energy supply related activities (e.g. planning, installation, operation & maintenance, financing for heating, etc.) (Bertoldi M. R., 2010).

ESC is suitable for district and small-scale heating networks so it is used for microCHP systems and particularly for geothermal applications since its energy can be measured with little effort through electricity or heat meters.

Then the ESC model could implement efficient supply from fossil fuels (suitable for microCHP) and renewable sources (apt for both ASHPs and principally GSHPs) for several facilities, including residential buildings. It is effective in reducing final energy demand since the ESCO pays for the final energy needed and it is remunerated just for its useful energy output.

Finally, this is the most popular form of contract and service and it is dominant in France, Italy and Spain and very popular in Germany and UK (Atanasiu, 2011).

2.2.4.3 EPC

Under an Energy Performance Contracting (EPC) business model, an ESCO guarantees energy cost savings in comparison to historical or calculated energy cost baseline (Würtenberger, 2012).

For its services and the savings guarantee, the ESCO receives performance-based remuneration in relation to the savings it achieves. The ESCO is responsible for the implementation and operation of the energy efficiency package and its own expenses and risk, according to the project specific requirements. At the end of the contract term, the facility owner benefits from the fuel energy cost savings, but all operation and maintenance amounts are included in the account.

This type of contract may realize savings for all energy shippers such as electricity, gas or water and typical sectors could be air conditioning systems, lighting or district heating connection. Therefore, it could be suited for microCHP or heat pumps technologies. In addition, EPC business model is increasing market share in most European countries, in particular Germany, UK, Italy and France (Atanasiu, 2011).

2.2.4.4 IEC

The Integrated Energy-Contracting (IEC) business model is a hybrid of ESC and EPC and its aims are reduction of energy demand through the implementation of energy efficiency measures and user behaviour and efficient supply of the remaining useful energy demand. As with ESC and EPC, IEC business model offers the building owner the choice to outsource technical and economic risks to a professional third party and to buy services instead of individual components (Würtenberger, 2012).

The ESCO is responsible for the implementation and operation of the energy efficiency package at its own expenses and risk, according to the project specific requirement defined by the client and the ESCO. (Bertoldi I. L., 2013) IEC is built on ESC model so it could be applicable in a similarly range of end-users sectors included residential buildings. Moreover, since IEC combines energy efficiency and energy measures all technologies drafted in the ESC and EPC business model descriptions are applicable comprised microCHP and heat pumps devices.

To sum up it is possible to define the main features of an ESCO and its principal aims independently by the typology of contracts. An ESCO is a means to deliver energy efficiency improvements to facilities through typical services (e.g. energy audits, engineering design, construction, operation and maintenance, etc.). ESCOs are traditionally focused on the public sector buildings. However, due to European policies on heating and cooling (European Commission, 2016), the ESCO market is increasingly expanding into residential buildings (chiefly multifamily buildings) sector in several countries (e.g. Germany, Estonia, France, Italy and Ireland as well) including deep retrofits, and in the district heating market (VTT Technical Research Centre, 2012).

Several barriers that could affect the diffusion of ESCOs include low awareness, lack of information about the ESCO concept, scepticism on the client’s side, non-supportive rules, public budgeting rules, etc., and may be overcome by enabling factors such as standard procedures and documents, dissemination of information for clients, policies, liberalization of the energy markets, etc.

In conclusion basic conditions for a strong ESCO market are:

- Creation of a long-term comprehensive energy efficiency programmes and facilitate financing;

- Creation of a clear legislative framework and establishment of appropriate market instruments and mechanisms;
- To educate the users and financial people is critical needed in most countries;
- To enhance the public acceptance of ESCOs with focused policy support and supportive policy frameworks;
- To establish and ESCOs association and enhance the collaboration with national energy agencies (Atanasiu, 2011).

2.2.4.6 Leasing

Leasing permits a building owner to use an energy installation without buying it. The installation is owned or invested in by another party usually a financial institution such as a bank and the building owner pays a periodic lease payment to that party (Activum, 2011). Generally, the financial institution remains owner of the resource during the lease period; there are several types of leasing possible depending on ownership and other economical, legal and fiscal conditions. It can be a central component of the business model on an ESCO which has limited own capital and therefore also limited access to debt but it could lease equipment from a financial institution and it can also be a central component of the business model of a company that introduces a specific new technology to the market. (Würtenberger, 2012)

Leasing could be applicable to all types of buildings even residential and it could be available especially for microCHP systems and for heat pumps.

Three of the most common leasing arrangements include:

- In the first situation shown in Figure 2.3 a building owner leases the technology, such as microCHP or heat pump, directly from a bank which owns the equipment. In exchange the building owner pays a periodic lease rate during the contract period which includes interest share (Würtenberger, 2012);

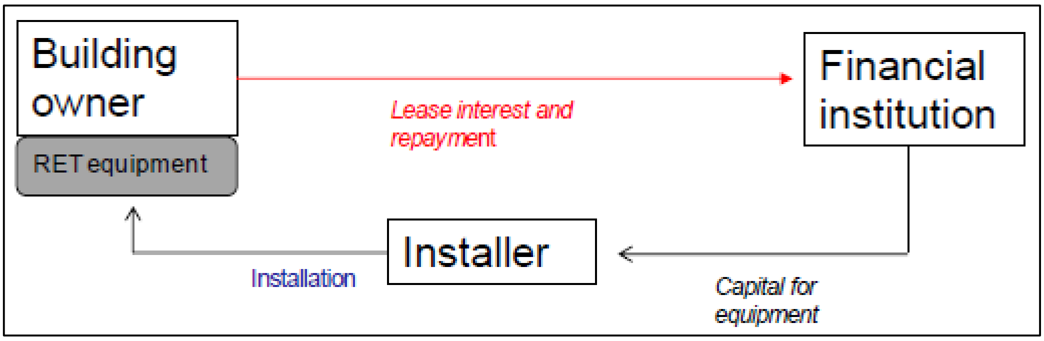

Figure 2.3. Lease agreement with directly involvement of financial institution.

Source: Bleyl, 2009

- In the second situation, an ESCO undertakes the negotiation with the financial institution, provides additional services to the building owner and remains the lessee of the equipment that is still owned by the financial institution itself. This situation is represent in Figure 2.4:

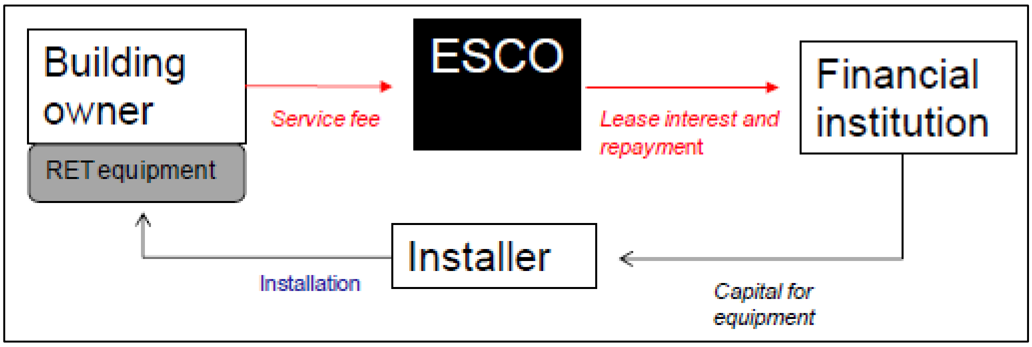

Figure 2.4. Lease agreement with involvement of an ESCO.

Source: Bleyl, 2009

- In the third option, a provider of microCHP or heat pump device leases the system to private customer and the technology provider usually also guarantees operation and maintenance service for the equipment as shown in Figure 2.5;

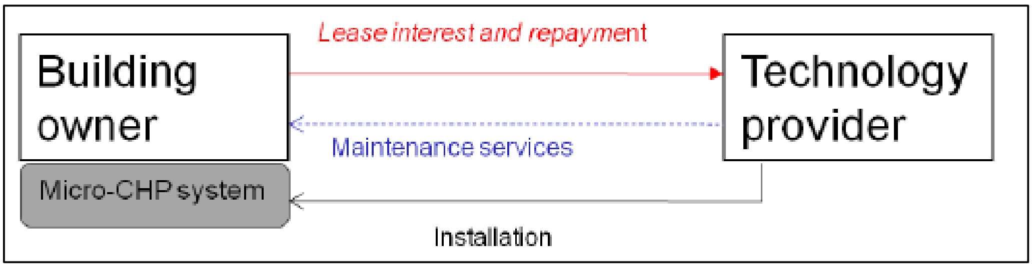

Figure 2.5. Leasing arrangement between a company distributing a technology and a building owner.

Source: Bleyl, 2009

The main advantage of a lease for a building owner is that the leased equipment can be used without having to invest in it. A maintenance contract could be offered in combination with the lease in order to reduce the effort required by the building owner and the technical risk for the lessor.

Generally, leasing is more expensive than taking a loan or financing the equipment otherwise (Würtenberger, 2012). Moreover, another element of weakness could be that banks are sometimes hesitant to offer leases since energy is not their core business and they may not want to assume operational risks.

2.2.4.7 Feed-in remuneration scheme

A feed-in scheme is a policy where the owner or the producer of energy receives a direct payment per unit of energy produced. This feed-in remuneration can be a *tariff* that covers the full generating costs or a *premium* that is a bonus for the owner to cover the financial gap accumulated for not using fossil fuels.

Feed-in based business models are applicable for all market segments, included residential buildings. The two main actors in a feed-in scheme are the institution that makes the payment available (government, network operator) and the recipient (homeowner, building manager or ESCO). The actual payment can be executed through a government agency, the energy supplier or through the network operator (Würtenberger, 2012). A feed-in scheme is a policy so the government fixes the tariffs and budgets and the cost of this support is recovered both from the government budget (i.e. from taxpayers) and from a network operator enlarges on energy bill (i.e. from energy consumers).

The main advantage of a feed-in based business model is that it has a predictable and stable long-term cash flow from a credit-worthy counterpart (Glifford, 2011). Conversely, the weakness is that tariffs set may deviate from the real costs. Investors that plan multiple investments over time do require trust in government to keep the stability of the feed-in system, which may be difficult if the government allows itself too much flexibility and changes from year to year (Würtenberger, 2012).

2.3 Electricity and gas prices in Ireland

The aim of this chapter is to explain the main aspects that affect electricity and gas prices in Ireland in order to describe the context in which this thesis work is carried out.

The increase in energy prices over the past number of years is a key concern for all energy consumers in Ireland, as they have influence on consumer spending and market competitiveness. Understanding the main contributing factors and the precise impacts of energy price changes are of key importance in developing appropriate, sensible and measured responses from business, householders and policymakers (Sustainable Energy Authority of Ireland, 2015).

Many factors influence energy prices in Ireland and, generally, in many other countries such as:

- *Global energy prices*: the most significant factor affecting energy prices in Ireland is the instability of global oil prices. This has particular effect on Ireland due to its high dependence on oil. In addition, there is the knock-on impact that oil prices have on other energy prices, in particular natural gas.

- *Fuel mix electricity generation*: This is particularly significant with respect to an electricity fuel mix that relies on internationally traded fuels like gas, oil and coal. During periods of volatile price movements in these fuels, there is a strong knock-on impact on electricity prices. (Sustainable Energy Authority of Ireland, 2015). Ireland has high overall dependency of electricity generation from fossil fuels (68%) with also high dependency on oil and gas generation (49%).

- *Investment in electricity and gas infrastructure:* It depends on the level of costs and the extent to which these costs are passed through to final consumer. Ireland depends on an extensive high voltage transmission network and a medium low voltage distribution network to transport electricity from generation locations to consumers. Gaslink has operated the natural gas transmission network in Ireland since 2008; according to the latest forecast from Gas Network Ireland (GNI) annual report (Gas Network Ireland , 2014), Ireland's transmission network infrastructure has sufficient capacity to transport anticipated gas demand to all end consumers into the near future.

- *Share of taxes in the prices paid by consumers in Europe:* Business can generally recover value-added tax (VAT). However, other taxes (including energy taxes, carbon taxes and climate-change levies) are typically not recoverable so the level of ex-VAT taxes is important especially when considering the business case for creating an in-country footprint. In addition, a Public Service Obligation (PSO) levy is charged to all electricity customers. The PSO levy support certain peat, gas and renewable generation plants, it is mandated by Government and approved by European Commission. (Eurostat, 2016).

- *Consumption volume (seasonal) effect on average unit price:* This effect is due to the fixed costs (standing charges, levies, etc.) that form a larger proportion of the average price based on the consumption volume. This is also known as a seasonal effect, and it is more pronounced in the household gas price than in the household electricity price and larger at the lower consumption levels.

- *Purchasing power:* When comparing prices of goods across countries, it is important to correct for differences in currencies and for the differences in income and living standards. This is particularly important when comparing prices paid by residential consumers. (Sustainable Energy Authority of Ireland, 2015). Another factor affecting gas and electricity prices in a country is the costs associated with labour and services.

2.3.1 Residential electricity prices

For households, electricity prices incorporate all charges payable that may include energy consumed, network charges, other charges (capacity charges, commercialisation, meter rental, etc.), all netted for any rebates or premiums due.

The Member States develop and implement cost-effective procedures to ensure the establishment of data compilation system based on the following rules (Sustainable Energy Authority of Ireland, 2015):

- Prices represent weighted average prices, using the market share of the electricity suppliers surveyed as weighting factors;

- Arithmetic average prices are provided only when weighted figures cannot be calculated;
- Weighted average prices are used in Ireland and represent the full market.

Market shares are based on the quantity of electricity invoiced by electricity supply undertakings to household end-users. If possible, the market shares are calculated for each band. The information used for calculating weighted average prices is managed by Member States, respecting confidentiality rules (Sustainable Energy Authority of Ireland, 2015). Three pricing levels are provided:

- Prices including taxes and levies;
- Prices excluding VAT and other recoverable taxes;
- Prices including all taxes, levies and VAT.

Electricity prices are surveyed for the categories of household end-user as shown in Table 2.17.

Table 2.17. Categories for residential end-use of electricity.
Source: (Eurostat, 2016)

Residential end-users	**Annual electricity consumption (kWh)**	
	Lowest	**Highest**
Very Small (DA)	<1000	
Small (DB)	1000	2500
Medium (DC)	2500	5000
Large (DD)	5000	15000
Very Large (DE)	>= 15000	

With regard to consumption bands, the most relevant for the majority of residential consumers are DC band (2500-5000 kWh per annum) and the DD band (5000-15000 kWh per annum). In the lower consumption bands the average price per kWh is higher because the standing charges and network charges form a larger proportion on the annual costs (Sustainable Energy Authority of Ireland, 2015).

Since DD band is very relevant for Ireland situation it is possible to report the trend of its electricity prices as explained by Figure 2.6.

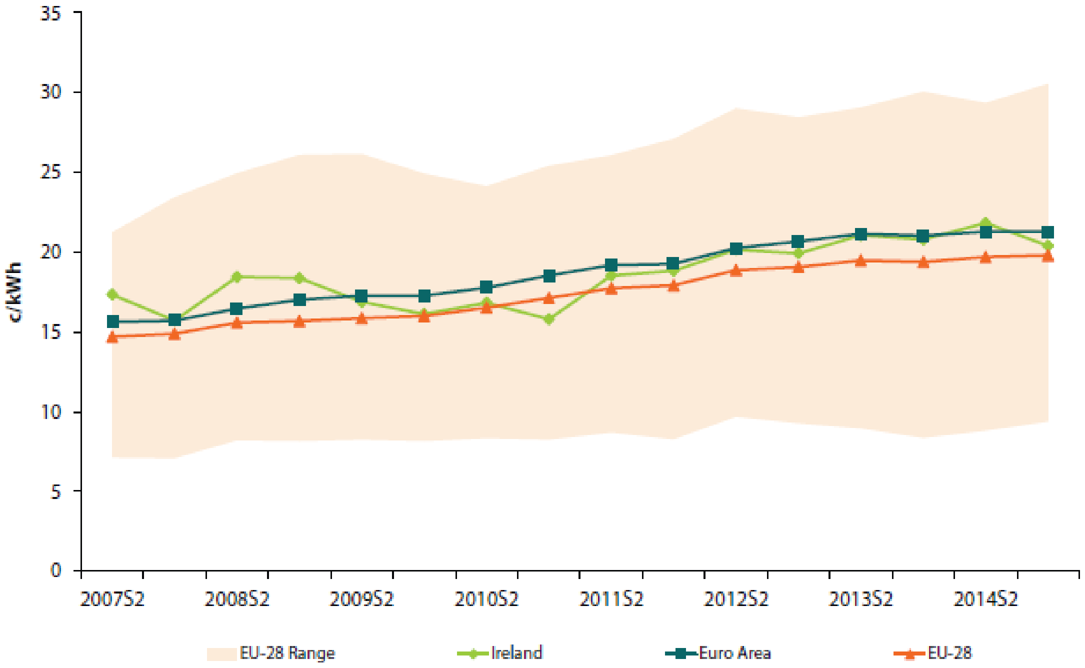

Figure 2.6. Residential electricity prices (all taxes included) in band DD (2nd semester 2007 to 1st semester 2015).

Source: (Eurostat, 2016)

As shown, prices in Ireland are generally fallen from the end of 2008 until the start of 2011. After that, prices in Ireland generally increased until the end of 2014 when it was 38% higher than the first half of 2011. In the last semester, prices in Ireland in this band fell by 6.6% (Sustainable Energy Authority of Ireland, 2015). The average price in the EU and the Euro Area has been steadily increasing over the whole period and the price being approximately one third higher at the end of the period compared with the start. For reference, consumers in bands DC and DD accounted for 81% of the residential electricity market, with band DD being the largest at 47% of the market, and DC the second largest at 34% (Sustainable Energy Authority of Ireland, 2015).

It is also possible to analyse the position of Ireland compared with the EU average residential electricity for all bands in the first semester of 2015 as shown in Figure 2.7.

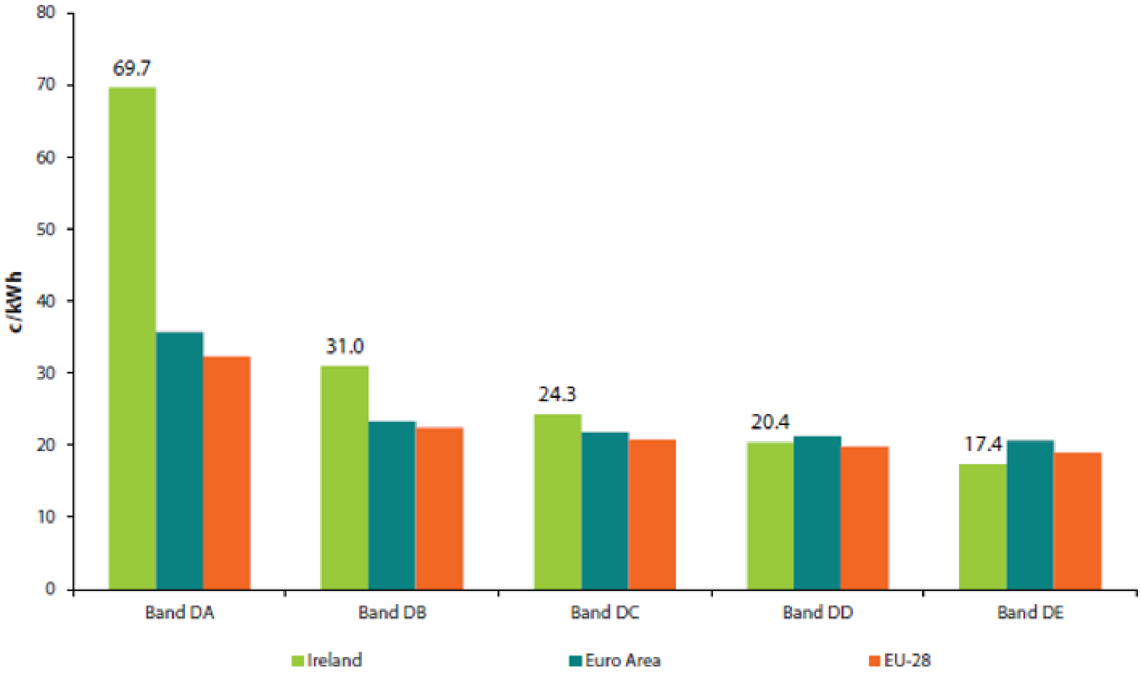

Figure 2.7. Residential electricity prices (all taxes included) in the 1st Semester 2015.

Source: (Eurostat, 2016)

The price level in band DA is high compared with the EU average. In the first half of 2015, Ireland was 17% above the EU average in band DC, up 7% points on the previous semester, and in band DD Ireland moved to being 3% above the EU average, from 11% above in previous semester.

2.3.2 Residential gas prices

For households, the situation is the same explained for electricity prices such as charges payable included, procedures implemented by Member States for a data compilation system based and the three pricing levels provided.

Gas prices are surveyed for the categories of household end-user as shown in Table 2.18.

Table 2.18. Categories for residential end-use of natural gas.
Source: (Eurostat, 2016)

Residential end-users	**Annual gas consumption (kWh)**		**Band share of residential gas consumption in Ireland S1 2015**
	Lowest	**Highest**	
D1 - Small	0	< 5600	6.5%
D2 - Medium	5600	< 56000	92.1%
D3 - Large	>= 56000		1.4%

With regard to consumption bands, it is possible to notice that the most relevant for the majority of residential consumers is the medium band referred as D2 and its trend is graphically presented in Figure 2.8.

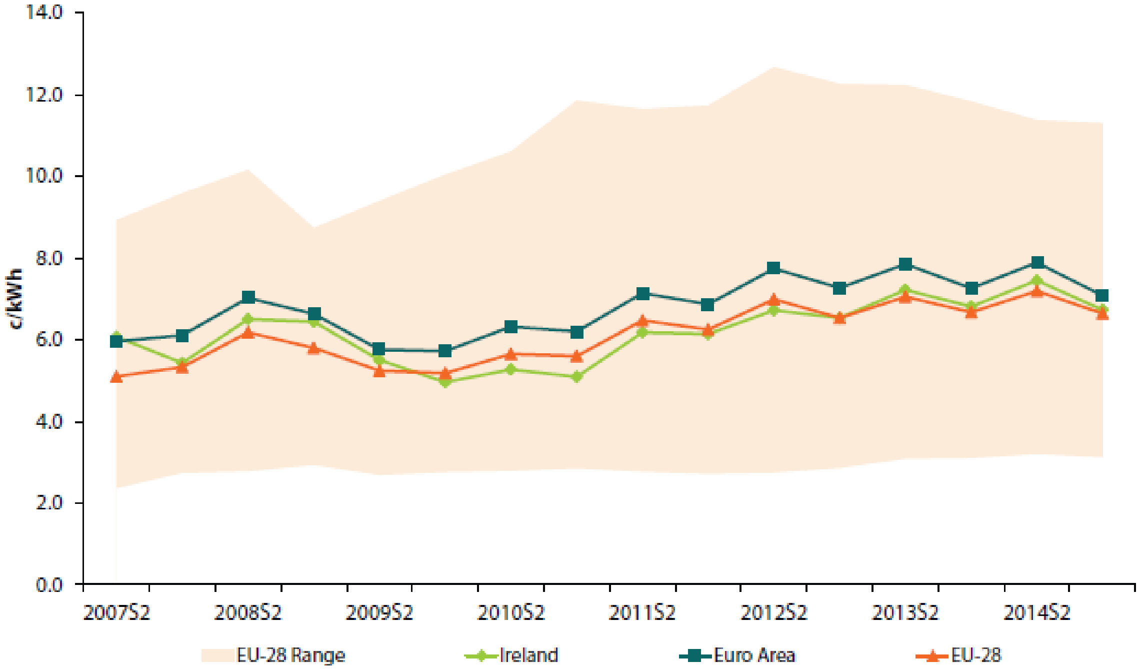

Figure 2.8. Residential gas prices (all tax included) in band D2 (2nd semester 2007 to 1st semester 2015).
Source: (Eurostat, 2016)

The gas prices in Ireland were higher than the EU average over the period between the second semester of 2007 and the second semester of 2009. Between the first semester of 2010 and second semester of 2012 the price in Ireland was below the EU average but it has been either at or above the average since then. In the last semester the price in Ireland was 1.4% above the EU average. Since the start of 2008, the price has been below the average Euro Area price.

As already done for electricity prices, it is possible to analyse the Ireland's position relative to the EU average gas prices to householders for first semester 2015 for each bands. This situation is shown in Figure 2.9.

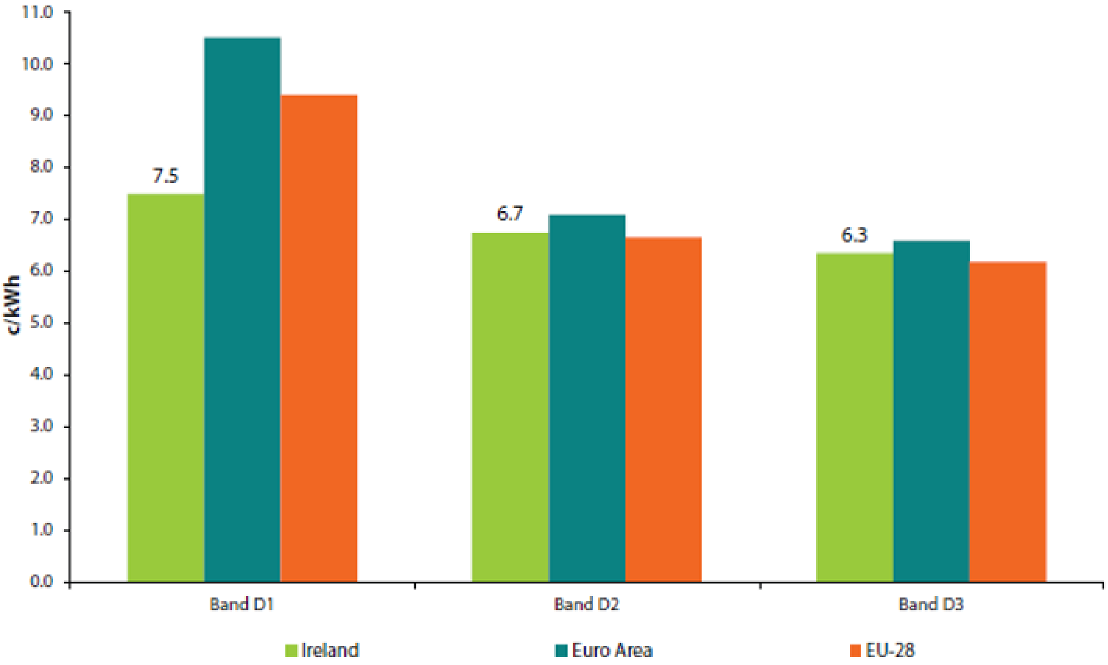

Figure 2.9. Residential gas prices (all taxes included) in the 1st semester 2015.
Source: (Eurostat, 2016)

During first semester of 2015 band D1 was below the EU average by 20% but bands D2 and D3 where above the average by 1.4% and 2.8% respectively (Eurostat, 2016).

2.4 Policies and regulations

2.4.1 EU Directive 2009/28/EC

In the European context, according to the EU Directive 2009/28/EC[11] the renewable energies are wind, solar, aerothermal, geothermal, hydrothermal, ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases. This Directive established a legislative common framework for the use of energy from renewable sources in order to limit greenhouse gas emissions. The fields of action defined in the Directive are energy efficiency,

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[11] European Union, 'Renewable Energy Directive 2009/28/EC', Brussels, 2009.

energy consumption from renewable sources, the improvement of energy supply and the economic stimulation in energy sector.

The Renewable Energy Sources Directive (RES) establish an overall policy for the production and promotion of energy renewable sources in the EU. It requires the EU to fulfil at least 20% of its total energy needs with renewables by 2020 to be achieved through the attainment of individual national targets (European Commision, 2016). Individual EU countries have different available resources and their own unique energy markets. This means that they will have to follow distinctive paths when it comes to meeting their obligations under the Renewable Energy Directive, including 2020 targets (European Commision, 2016). In their national action plans, they explain how they intend to do this. In particular, the plans cover individual renewable energy targets for the electricity and heating sectors and each Member State is required to complete the template.

2.4.2 National Renewable Energy Action Plan (NREAP)

In Ireland, National Renewable Energy Action Plan (NREAP) is the submission required under the Directive and follows the format (data and questions) required in established template (NREAP, 2009). The NREAP was published in 2010 and sets out the Government's strategic approach and concrete measure to deliver on Ireland's 16% target under Directive 2009/28/EC.

The development of renewable energy is central to overall energy policy in Ireland. They reduce dependence on fossil fuels, improve security of supply and reduce greenhouse gas emissions creating environmental benefits and contributing to national competitiveness.

The Government's ambitions for renewable energy and the related national targets are fully commensurate with the European Union's energy policy objectives and the targets addressed to Ireland under the Renewable Energy Directive. Ireland's energy efficiency ambitions (20% by 2020) are duly reflected in the NREAP (European Commision, 2016).

National sub-targets in each of the energy end-use modes of electricity and heat have been set by Ireland to achieve this overall target. These are a 40% penetration of renewable electricity in gross electricity consumption and a 12% penetration of renewable energy consumption in the heat sector (Clancy, Renewable Heat in Ireland to 2020, 2015).

2.4.3 Decision No 406/2009/EC

Ireland signed the EU's Effort Sharing Decision (Decision No 406/2009/EC) which set 2020 targets for EU Member States on greenhouse gas emissions from sectors that are not included in the EU Emission Trading Scheme (EPA, 2015) (European Union, 2009). This sectors covers, among others, built environment (residential, commercial/institutional) and Ireland's target is to achieve a 20% reduction by 2020 on 2005 levels. In addition, there are binding annual emission limits for the period 2013-2020 to ensure a gradual move towards the 2020 target. Any overachievement of the emission limit in the particular year can be banked and used towards compliance in a future year (EPA, 2015).

2.4.4 Heat pumps regulatory framework

The Directive on the Promotion of the Use of Energy from Renewable Sources (RES Directive), EC/28/2009 recognises all heat pump typologies as renewable energy technologies whether they use air, water or the ground as an energy source. As already observed, the shift from the use of energy from non-renewable to the use of energy from renewable sources is supported by several measures. Especially, the promotion of renewable energy will have a positive impact on the heat pump market. However, examining the legislation shows that the support for renewable energy is usually implemented at a general level and is not specific to heat pumps.

The European legislation has an impact on the national legislation of the Member States and an indirect impact on heat pump sales. Following, some of the major legislative acts currently in place on the European level are reported.

2.4.4.1 The RES Directive

The Directive on the Promotion of the Use of Energy from Renewable Sources (RES Directive) can be reviewed as having a positive impact on heat pump technology, as it acknowledges heat pumps as a technology that makes ambient energy from air, water and ground useful (Bettgenhäuser, et al., 2013). A minimum requirement on seasonal efficiency to be reached at standard rating points is set by the RES Directive and only heat pumps that reach a minimum efficiency (SPF of 2.53) will be counted.

2.4.4.2 Energy Performance of Buildings Directive (EPBD)

The Energy Performance of Buildings Directive (EPBD) 2010/31/EU is focused on the improvement of energy performance of buildings, building elements and technical systems. This directive has already been transposed into national law by Member States.

The EPBD, as the RES Directive, has a positive impact on the development of heat pumps since EPBD acknowledges heat pumps as a technology that transfer heat from natural surroundings to buildings. Moreover, it sets minimum requirements for the building envelope and it also consider available heating alternatives prior the construction (Bettgenhäuser, et al., 2013).

2.4.4.3 Energy Efficiency Directive (EED)

The Energy Efficiency Directive (2012/27/EU), which must be implemented in EU Member States by 5 June 2014, aims at increasing the efforts currently made by Member States to use energy more efficiently and it contributes directly to the 20/20/20 target of 20% primary energy reduction by 2020. The future impact of the EED on heat pump technology is yet unclear, but can be expected to be a rather positive impact. The fact that the EED mentions the efficiency potential of buildings and of distributed energy production is essential for the advancement of heat pumps. Nevertheless, it is more focused on CHP and district heat implementation. Therefore, the impact on heat pump devices is not as big as for other policies (Bettgenhäuser, et al., 2013).

2.4.4.4 Heat pump regulatory framework in Ireland

In Ireland, as in European Union, specific policies and directives currently do not exist regarding heat pumps. Generally, policies and environmental targets refer to renewable energies and the major parts of them are quite old.

Under the European Commission’s “20-20-20” strategy, Ireland is committed to a 20% reduction in final energy consumption, as compared to average energy use in the period 2001-2005, a 20% reduction in greenhouse gas emissions from 2005 levels and an increase in the contribution of renewables to final energy consumption to 16% by 2020 (Irish Academy of Engineering, 2013).

According to Academy of Engineering, the Policy Advisory demonstrates how these reduction goals can be achieved through a strategic rebalancing of Government energy policy between 2013 and 2020. In the residential sector, Academy of Engineering recommends acceleration of the national insulation-retrofitting programme, in particular the retrofitting of heat pumps, these to operate in conjunction with existing oil-fired central heating, but reducing oil use by approximately 90% (Irish Academy of Engineering, 2013). From 2006 and 2011, was active the Renewable Heat Deployment Programme (ReHeat) a financial measure that aimed to increase the deployment of renewable heating technologies (such as heat pumps) in several sectors (including residential).

In March 2007, the Irish Government Launched the Energy White Paper, a practical action-based strategy to promote a sustainable energy future, efficient prices to consumers and fostering the renewable sources penetration in the energy market. Between 2007 and 2009, the Greener Homes Schemes provides grant assistance to homeowners who intend to purchase a new renewable energy heating system for either new or existing homes (SEAI, 2011). The scheme finished its budget in 2011 and was administrated by SEAI and aimed to increase the use of renewable energy, in particular heat pumps, in Irish homes. A large number of manufacturers' companies joined the project.

2.4.5 MicroCHP regulatory framework

The European Union CHP Directive 2004/8/EC (European Parlament, 2009), approved in February 2004, is the first European Directive that created a favourable environment for CHP installations, contained definitions for micro, small and large scale CHP.

The European Commission published Decision 2007/74/EC (Official Journal of the European Union, 2006) establishing harmonised efficiency reference values for separate production of electricity and heat in December 2006 (SEAI, 2014). MicroCHP is recognised at the EU level in legislation such as Energy Efficiency Directive 2012/27/EU (EED) in order to contribute to reaching EU's energy savings target. Moreover, the faster rollout of MicroCHP would reduce emissions attributed to the residential sector, while increasing the energy performance of existing buildings as required in Energy Performance in Buildings Directive 2010/31/EU (EPBD) (COGEN Europe, 2014).

In particular, the EED gives them the opportunity to assess current legislation and develop an appropriate policy structure that is supportive of microCHP technologies (COGEN Europe, 2014).

2.4.5.1 MicroCHP regulatory framework in Ireland

The Energy (Miscellaneous Provisions) Act of 2006 (Irish Statute Book, 2006) is the transposition of the EU CHP Directive into Irish law. On 25th October 2012, Directive 2012/27 /EU (EED) of the European Parliament repealed the CHP Directive. Since, this Directive places energy efficiency at the core of the EU Energy 2020 strategy, it recognises that high efficiency CHP, together with district heating and cooling, has significant potential for achieving primary energy savings.

Moreover, it disposes a number of obligations on Member States (Ireland included) that they establish mechanism for guaranteeing the origin of electricity from cogeneration and provide priority access for electricity generated from high efficiency cogeneration (SEAI, 2014). Transposition of the Directive in Ireland was completed in 2014 by two statutory instruments, SI 131 and SI 426. Finance Act 2012 (Irish Statute Book, 2012) made a provision for a partial relief from fossil fuels and a fuel relief from peat, using heat and power cogeneration. Tax reliefs, available also for microCHP plants, meet the requirements for high-efficiency cogeneration under 2004/8/EC of the European Parliament. The relief is given by means of repayment to the consumer of the fuel for microCHP plant and there is a further relief from electricity tax for electricity used for combined heat and power generation (SEAI, 2014).

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Chapter 3: Methodology

The previous chapters have mainly provided a review about the state of art of heat pumps and microCHP devices and business models available for these two technologies.
This chapter focuses on the methodology used for getting results that represent the basis for all analysis made about the two different technologies.
The aim of the chapter is to present the procedures adopted for developing the economic and environmental comparison between heat pumps and microCHP and the path followed to achieve these results. The analysis can be divided into three main parts, summarised in Figure 3.1:

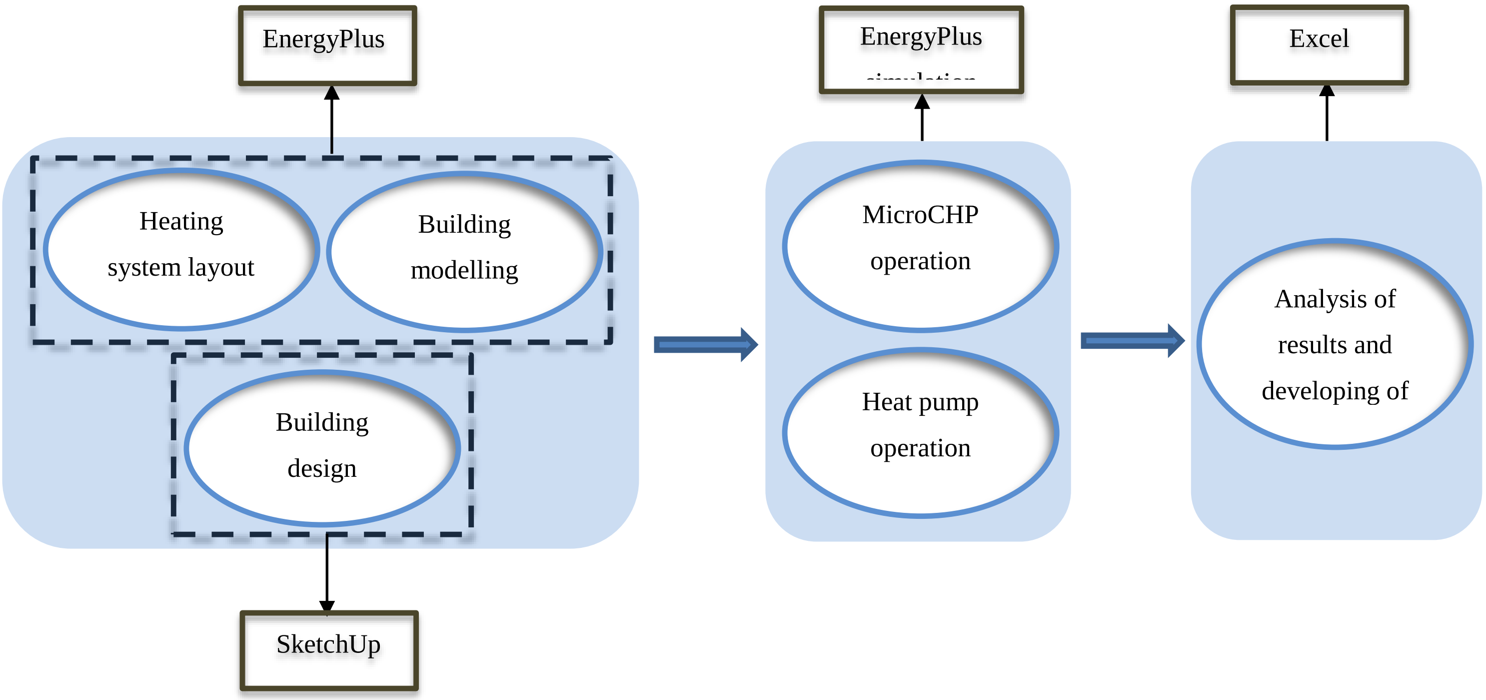

Figure 3.1: Methodology structure adopted in the analysis.

The first part principally involved the physical modelling of the overall system and it could be divided into three steps that are, first of, the residential building modelling i.e., using SketchUp software the building is designed and modelled following a typical Irish bungalow features. What is gained after this step is the detached house that will be described precisely in the Chapter 4. Secondly, the heating system has been modelled following the building's features, considering that heat in the house is supplied by a floor-heating system and a tank is present in order to provide domestic hot water. The layout remains the same for the two technologies and the only thing that changes is naturally the fuel supply.

After that, it is possible to create the EnergyPlus model after the data entry step. In particular, in this part all parameter fields have been filled in the EnergyPlus "Edit-IDF Editor" in order to represent a residential building, the climate and heating system technical data. Two separate files were created to capture the heat pump and microCHP models.

In the second part, there is the software simulation that allows the creation of two different Excel files for each technologies. In the first one, called "Meter" it is possible to evaluate the whole consumption of electricity (for the heat pump case) and the whole gas consumption and electricity produced (for the microCHP) for every single hour of the year. In addition, it is possible to analyse the hourly electricity consumption for each item of the house i.e. facility, lighting, equipment, etc. that both devices have to supply in the same way since the electricity demand of the house does not change. The second Excel file that we can obtain after the software simulation is called "Table" and reports data such as electricity consumption of the house related to the building's features. Therefore, it is possible to analyse, for instance, how electricity consumption is divided among different items in the whole year or how energy gains and losses are split in all rooms of the house.

In the third part of the analysis, results returned by EnergyPlus' simulations are used to achieve the goals of this thesis work. In particular, in order to make a comparison between heat pump and microCHP devices we carried out an economical and environmental analysis after having studied the differences between their energy performances.

In order to examine their energy performances it is necessary to compare their electricity profiles that are obtainable by simulation's results. Then, for environmental criteria, we calculate the annual CO_2 production of both technologies and the method followed will be explained in Chapter 5.

Subsequently, to assess the economic criteria we need to find out which is the most expensive devices during their operation in the whole year. Again, the method followed will be illustrated in Chapter 5.

Finally, a Net Present Cost (NPC) analysis will be used to measure heat pump and microCHP with a conventional heating boiler. This analysis and its results are described in Chapter 5.

Chapter 4: Model description

4.1 Introduction

The aim of this study is to examine options for heating a residential building considering air-source heat pump and microCHP devices, and comparing them according to three criteria: energy efficiency, economic value and environmental impact.

The model used for the residential house is considered as located in Ireland and the analysis was carried out using EnergyPlus and is described in the HVAC system section below.

In Ireland residential buildings account for 34% of total electricity energy consumption according to SEAI (O'Leary, Howley, & O Gallachoir, 2008). It is expected that in the future electricity demand patterns of the residential sector will change due to development of smart grid initiatives and the increasing deployment of renewable energy system (RES) installations (Pallonetto , Oxizidis, & Duignan, 2013).

The deployment of the smart grid allows buildings to provide flexibility as the ability to shift electrical power consumption, which is normally aligned with real-time energy demand, to other non-peak times (Pallonetto, Fabiano; Oxizidis, Simeon; Finn, Donald, 2014) .

Smart grid energy management schemes can contribute in decreasing the carbon footprint of the consumer, optimising the building energy systems operation and evaluating appropriate demand response schemes.

4.2 Building description & plant layout

The first step undertaken in the model building was characterising the structure of the house and its size in order to examine the heat and the electric demand for the whole construction. For this goal the software EnergyPlus has been used.

The following part of the thesis will report the main assumptions adopted for the building structure, heat gains and heat losses, ventilations and infiltrations and the plant layout.

4.2.1 Location and architectural design

The building is a detached house located in Dublin at 53.43° north latitude and 6.4° west longitude with an elevation of 85 m. The weather station is located at UCD, Belfield Dublin and the climate data was for the 2014; this data was used at the input for the building energy simulation analysis.

Weather and climate data for the selected site were provided by the software EnergyPlus, taken from the International Weather for Energy Calculations (IWEC) data set.

Moreover, the simulation is carried out for 2014 therefore all climate data are referred to that year. A graphical re-elaboration of the outdoor temperature and solar radiation values for the select location are shown in Figure 4.1. In particular, the annual average outdoor air temperature in the site is 9.77°C.

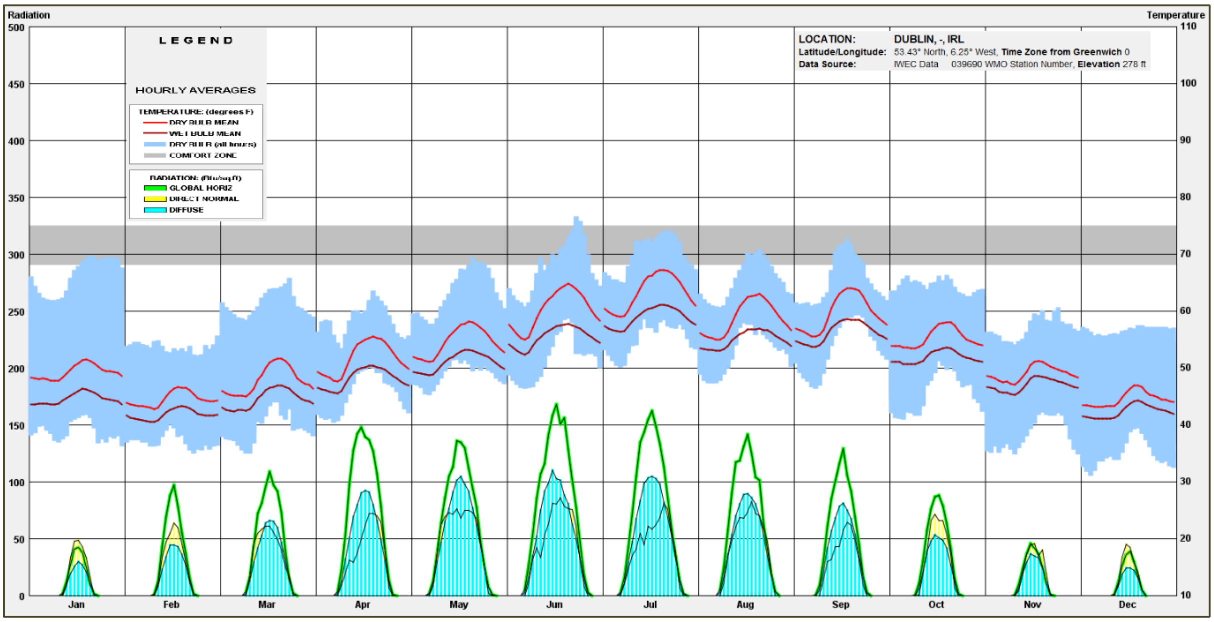

Figure 4.1. Values of monthly average temperature and solar radiation for Dublin for 2014.

Source: IWEC

The house has a total surface area of 160 m^2 and a total volume of 403 m^3. The U-Values of the different building components differ from the current Irish building regulation maximum values (2011) since the facility is not insulated. Some of the main features for the building are reported in Table 4.1.

Table 4.1. Summary of the building characteristics adopted in the model.

Building characteristics	**Building values**
Total floor area (m^2)	160
Volume (m^3)	403
Gross wall area (m^2)	183.6
Gross wall area facing North (m^2)	51
Gross wall area facing South (m^2)	51
Gross wall area facing East (m^2)	40.8
Gross wall area facing West (m^2)	40.8
Roof area (m^2)	97.58
U value, exterior walls(W/m^2K)	4.335
U value, roof (W/m^2K)	6.301
U value, windows (W/m^2K)	3.165
U value, floor (W/m^2K)	0.163

Moreover, the gross window-wall ratio for each side of the building is sumarized in Table 4.2.

Table 4.2. Gross window-wall ratio for each side of the building.

	Total	**North (315° to 45°)**	**East (45° to 135°)**	**South (135° to 225°)**	**West (225° to 315°)**
Gross window-wall ratio [%]	22.24	0	49.89	0	50.21

The gross wall area is defined as the area of a wall including any openings, such as doors or windows in the wall (http://standards.phorio.com/, 2011). The total amount of this parameter in the building is 183.6 m^2 with the same value for north and south (51 m^2) and for east and west (40.8 m^2). The window to wall ratio of a building is defined as the percentage of its façade taken up light-transmitting glazing surfaces, including windows and translucent surface such as glass bricks. Only façade surfaces are counted in the ratio, not roof surfaces (http://standards.phorio.com/, 2011).

The overall window to wall ratio is 22.24% with 49.89% and 50.21% ratio on the east and west faces respectively. It is important to notice how this value is 0 on the south and north faces since in these sides windows are not present.

The house has 14 rooms and each one is considered a specific thermal zone. Table 4.3 describes some features for each room.

Table 4.3. Performance zone summary in the building for each room.

Room	**Area [m^2]**	**Conditioned (Y/N)**	**Volume [m^3]**	**Windows Glass Area [m^2]**	**Lighting [W/m^2]**	**People [m^2 per person]**	**Plug and process [W/m^2]**
Kitchen	14.1	Yes	36.66	3.32	75	1.77	736.3298
Utility	5.4	Yes	14.04	0	43	16.18	917.6852
Dining	18.5	Yes	48.1	5.51	48	4.68	12.5
Study	10.8	Yes	28.08	3.03	59	0.75	25.7407
Hall	12.7	Yes	33.02	0	43	16.18	12.5
Living	18.5	Yes	48.1	5.22	214	0.56	29.1486
Bath	6	Yes	15	1.44	59	1.8	12.5
Bed1	9	Yes	17.5	3.74	59	3.27	12.5
Bed2	11.33	Yes	28.33	3.74	75	3.27	12.5
Landing	17.66	Yes	44.15	0	43	16.18	12.5
Ensuite	4.01	Yes	10.02	0	59	1.8	12.5
Bed3	16	Yes	40	4.8	102	1.8	20.25
Bed4	16	Yes	40	4.8	91	1.35	12.5
Attic	80	No	82.43	0	/	/	/
Total	160	/	403	35.6	82.1174	1.7	110.4313

From this table it is possible to study which are the rooms where there are main demands and consumptions during the year. For instance, in the living room there is the largest requirement for lighting (214 W/m^2) while in the utility room and in the kitchen there are the main demands for plug and process that is the electricity spent for electric equipment.

In addition, the "people" column show which are the rooms that could be the highest traffic areas. These rooms are utility, hall and landing room.

Besides, a schematic representation of the house designed using SketchUp software is reported in Figure 4.2.

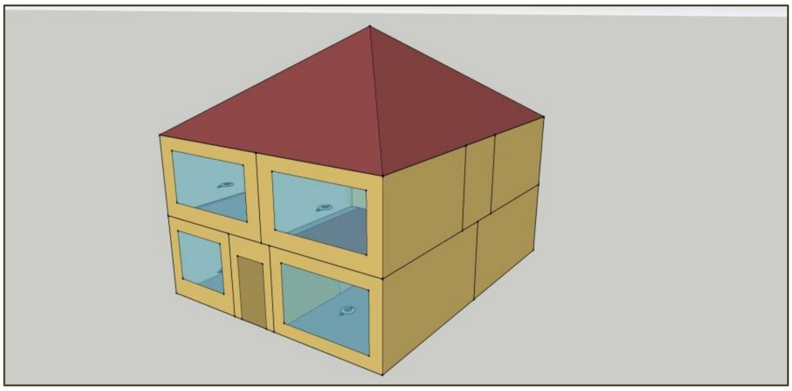

Figure 4.2. Residential building structure adopted in the model.

Then it is also possible to present two other figures that represent the first and the second floor of the building in order to understand how the structure is inside.

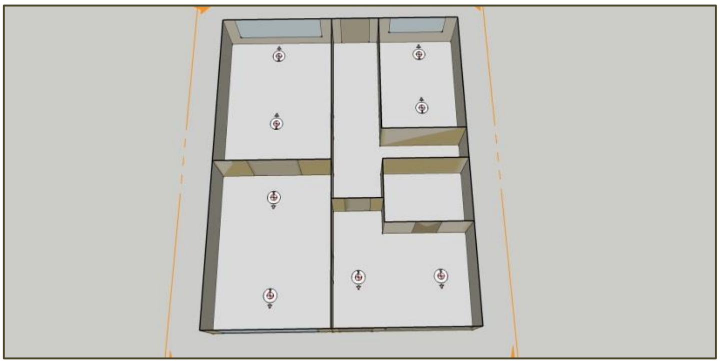

Figure 4.3. First floor plant of the building.

Figure 4.4. Second floor plant of the building.

4.2.2 HVAC system & plant layout

For space heating the house requires a calculated design load of almost 15 kW while the user design load is higher than 17 kW. In the analysis the house is equipped with an air-source heat pump or with an internal combustion engine microCHP device that supply the heating demand in the two different situations. Both of these two appliances were modelled with EnergyPlus using physical parameters taken from the software library in order to estimate their performances in heating the house.

A floor heating system is used to heat the house in each room exclusive of the attic. There are 26 mixing zones considered in the analysis (i.e. simple air exchange from one zone to another). The mixing zones are considered to affect the energy balance of the “receiving” zone and will not produce any effect on the “source” zone.

Both heat pumps and microCHP systems are composed of heating primary loop and heating secondary loop as shown in the following figures.

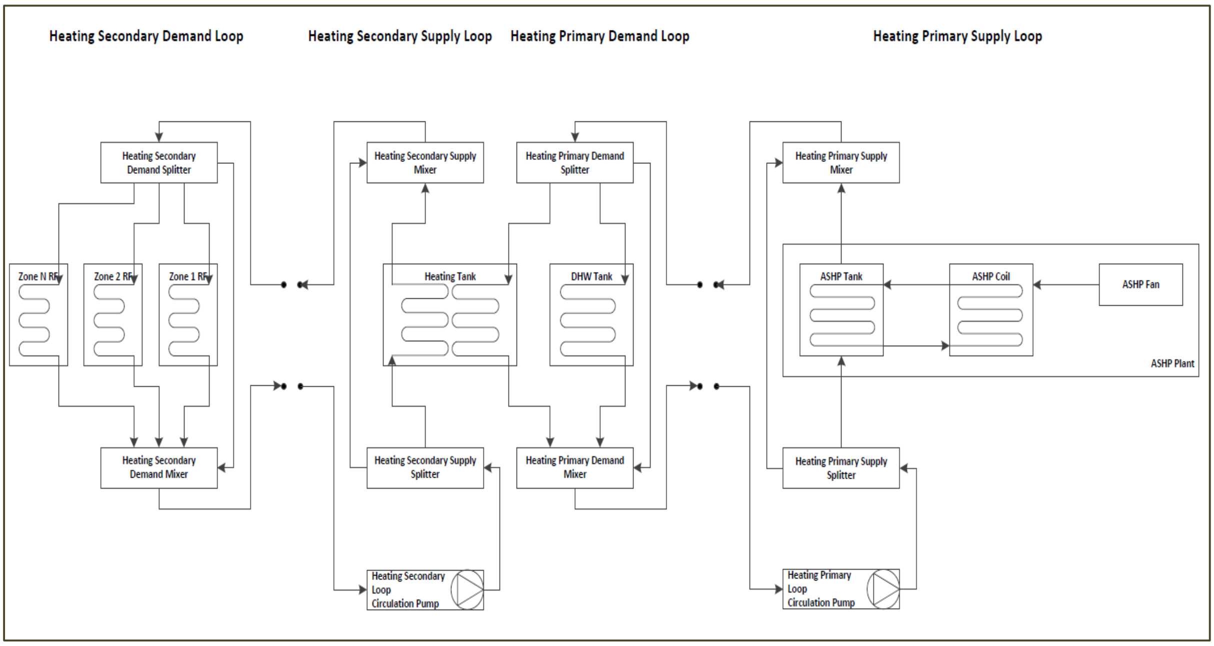

Figure 4.5. Air to water heat pump heating system.

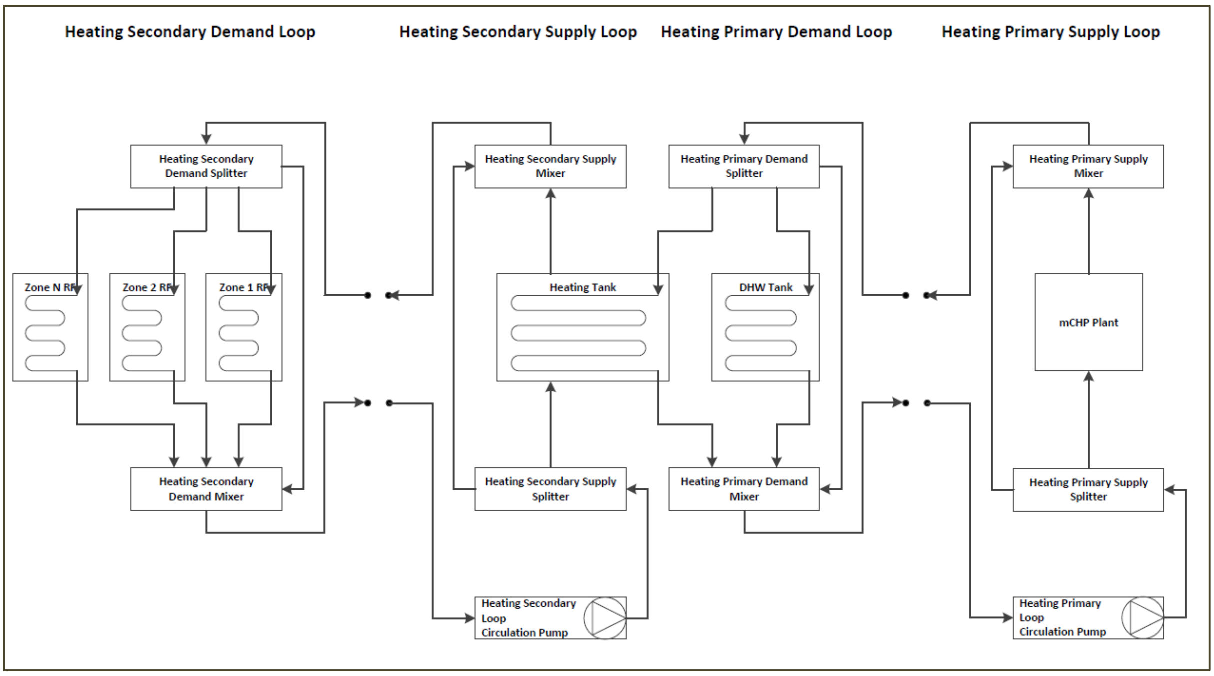

Figure 4.6. Internal combustion engine microCHP heating system.

As illustrated the heating system is the same for both technology. The only difference is, naturally, devices that produce the heat and the condition in which they work. For the microCHP system the exit temperature of the primary loop is 85°C while for the heat pump system is 70°C. Then the exit temperature of the secondary loop is 75°C for the microCHP system and 67°C for the heat pump one.

4.2.2.1 Heat pump model

The heat pump device is composed by a heat pump water heater (HPWH) heating coil, air-to-water direct-expansion (DX) system which includes a water heating coil, evaporator air coil, evaporator fan, electric compressor and water pump.

Rated heating capacity (thermal output) of the system is 14500 W with a rated COP of 3.9. The rated evaporator inlet temperature of dry-bulb air is 10°C while the rated condenser inlet temperature of water is 35°C.

The ASHP tank that is the heat pump water heater has a volume of 0.1 m^3, it requires electricity as fuel and it is located in the utility room.

The ASHP has a constant volume fan intended to cycle on and off based on heating control or other control signal. It has a total efficiency of 0.7 and it is coupled with a motor that has an efficiency of 0.9.

4.2.2.2 MicroCHP model

The microCHP generator is an internal combustion engine fed by natural gas located in the utility room that can produce a maximum electric power of 7500 W. It has a rated thermal to electrical power ratio of 2.444.

4.2.3 Occupancy profile

The occupancy profiles, use of electric equipment and lights, domestic hot water (DHW) use patterns and the respective distribution of internal gains were calculated. People, lights and electric equipment have been evaluated as internal gains. To build the necessary profile, a time of use activity survey was utilised. The profiles were calibrated with the convenient occupant adjustments to better replicate the real life activity patterns.

The occupancy profile was adjusted according to the working time of the occupants and their typical weekend and evening activities. The appliances typical time of use was also tuned according to their habits. Specific schedules based on typical use were adopted for electrical equipment such as washing machine and dishwasher. The building is naturally ventilated just by opening the windows and exhaust air extraction fans are not present except in the kitchen and the bathroom. For this reason if the sum of infiltration and ventilation is calculated for each room the values obtained are pretty similar without great differences among them. In particular one can analyse how the living room has the lowest value of 1.13 ACH (Air Changes per Hours) while the highest values are in the kitchen with 1.309 ACH and mainly in the landing with 1.347 ACH as shown in the Table 4.4.

Seasonal (between winter and summer) and daily (between night and day) variations of both infiltration and ventilation were considered.

Table 4.4. Infiltration and ventilation for each room.

Room	***Infiltration [ach]***	***Simple ventilation [ach]***	***Sum of infiltration and ventilation [ach]***
Kitchen	0.751	0.558	1.309
Utility	0.763	0.563	1.326
Dining	0.745	0.547	1.292
Study	0.739	0.54	1.279
Hall	0.741	0.546	1.287
Living	0.786	0.344	1.13
Bath	0.774	0.482	1.256
Bed1	0.798	0.578	1.376
Bed2	0.778	0.491	1.269
Landing	0.776	0.571	1.347
Ensuite	0.764	0.553	1.317
Bed3	0.78	0.54	1.32
Bed4	0.785	0.556	1.341

4.2.4 Heat gains and losses

In order to evaluate how internal gains and losses are divided into the building it has been analysed the situation for the living room during wintertime and summertime. In particular, different situations in January and July were studied as outlined graphically in following figures.

4.2.4.1 Heat gains and losses in wintertime

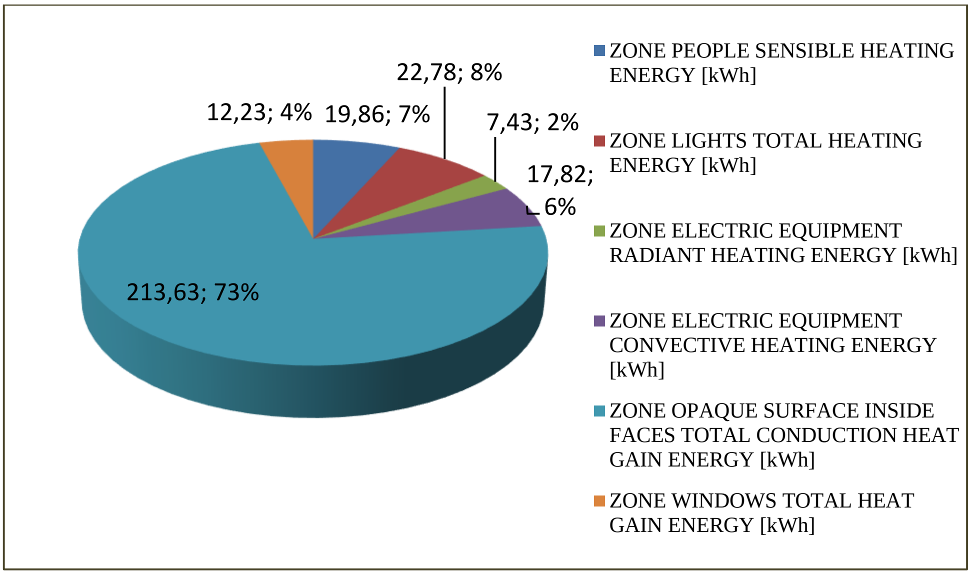

Figure 4.7. Heat gains values and percentage for each item in January in the living room.

During January the main entry for energy gains comes from heat conduction through opaque surface within the floor heating system supplied by heat pump or microCHP devices due to the fact that the building is not insulated. If the building was a passive house this percentage would have been much lower. It has the highest percentage (73% and 213.63 kWh of absolute value) of energy gained inside the building followed by total heating (both latent and sensible) derived from lights (8%, 22.78 kWh) and by sensible heat from people (7%, 19.86 kWh). Other entries, which include convective heating from electrical equipment, total heat from windows and radiant heating from electrical equipment, have really low percentages.

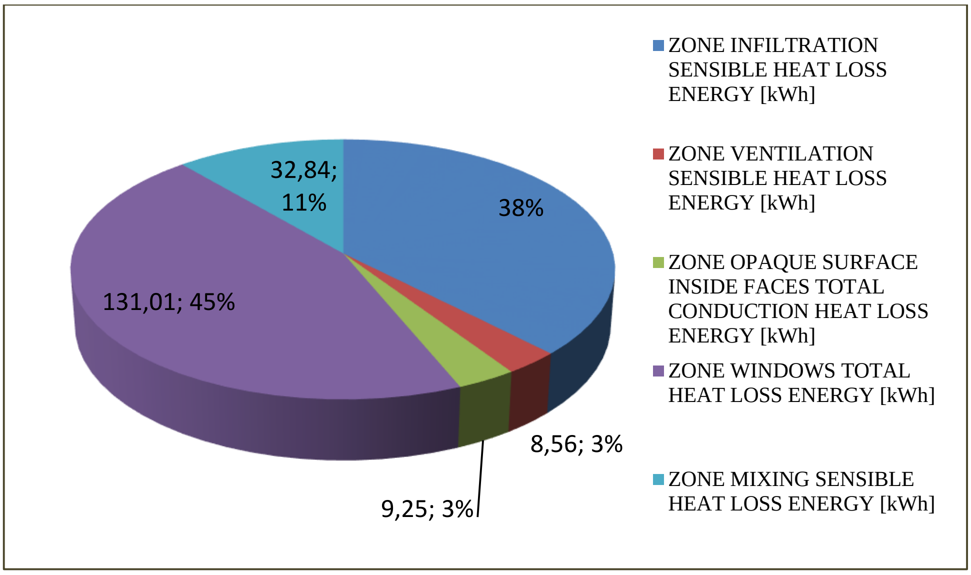

Figure 4.8. Heat losses values and percentage for each item in January in the living room.

For energy losses, the highest percentages are related to windows heat losses (45%, 131.01 kWh) and sensible heat losses due to infiltrations (38%, 109.62 kWh). This tendency is easily comprehendible due to the strong difference of temperature between internal house and temperature of environment outside that is low in January.

Moreover, it is possible to observe how total conduction heat losses from opaque surfaces have a small value since the heating system is functioning for an extended period of time and produced goes from the wall toward the internal space.

Another important aspect of energy losses is represented by the mixing sensible heat (11%, 32.84 kWh). This is difference of temperature between two adjacent rooms. In this case this entry is not negligible since the living room has potentially a higher temperature than rooms beside as it is more consistently occupied and therefore warmer.

4.2.4.2 Heat gains and losses in summertime

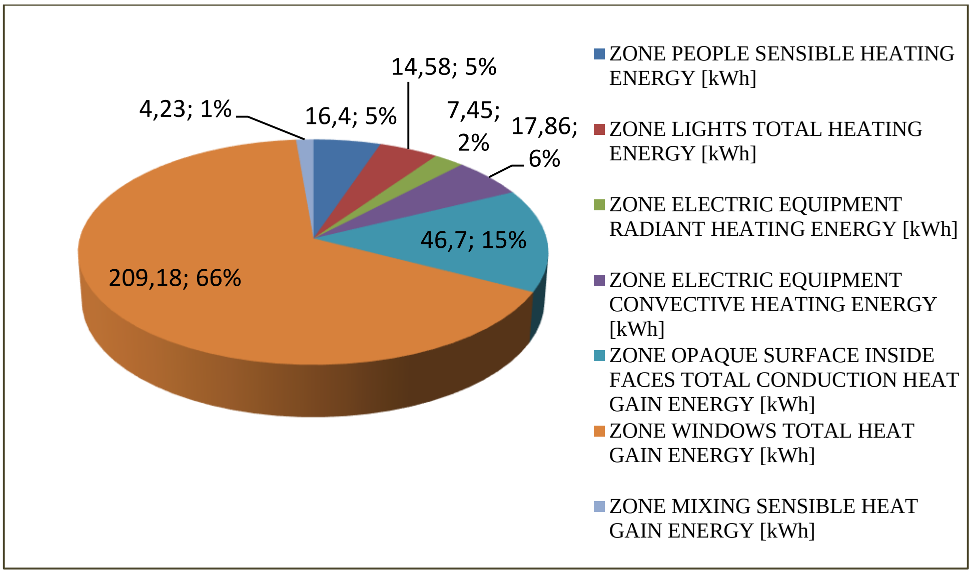

Figure 4.9. Heat gains values and percentage for each item in July in the living room.

This situation is less interesting since during summertime the house is not heated. However, from the energy gains pie chart it is possible to notice that the largest item is represented by the total heat through windows (66%, 209.18 kWh) due to the greater presence of solar radiation compared with wintertime period. A considerable value comes from the total conduction heat through opaque surface inside faces (15%, 46.7 kWh) which indicates that there is radiation heat passing through the wall as a result of higher temperature outside than inside the house.

The other values of energy gains that have negligible percentage are radiant and convective heating energy from electrical equipment, total heat energy from lights and sensible heating energy from people.

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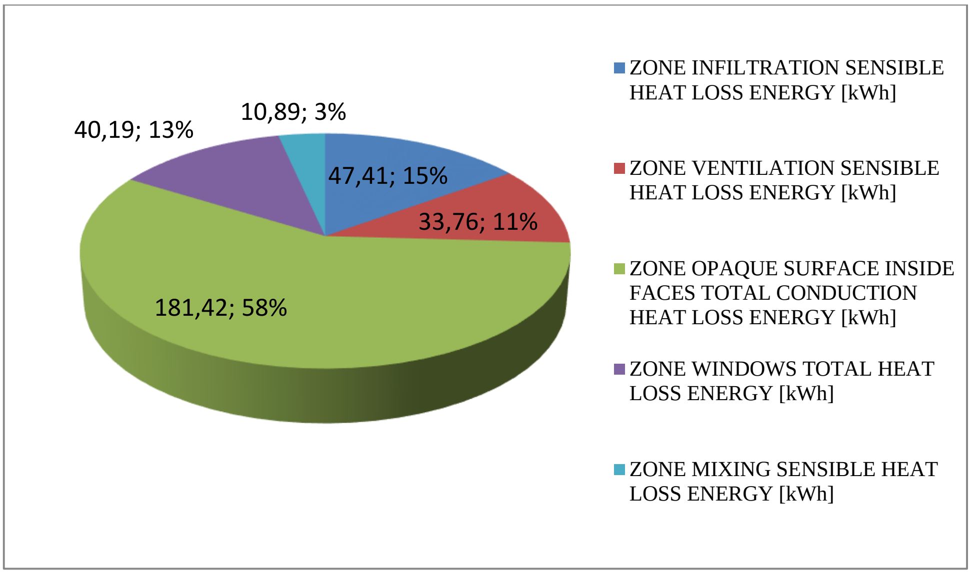

Figure 4.10. Heat losses values and percentage for each item in July in the living room.

For heat losses, one can see the opposite situation compared with the graph of gains since the main entry of energy loss is the total conduction heat through opaque surfaces (58%, 181.42 kWh) since radiation goes from internal rooms toward external environment that has higher temperature. Through walls there is a higher amount of heat lost that gained during summertime.

Other entries for heat losses are result of sensible heat infiltration (15%, 47.41 kWh) and also of the total heat lost through the windows (13%, 40.19 kWh). However, the total amount of heat gained through the windows is much higher than lost in this period.

Another item of loss is by cause of sensible heat ventilation (11%, 33.76 kWh) even if its percentage is pretty low. For sensible heat ventilation this is loss of heat that is due to air passing through doors or windows openings.

Finally, the lower item that affects energy loss here is mixing sensible heat that has a negligible percentage. Compared with January this situation is different since during summertime the whole house has a temperature that is similar in all rooms while during wintertime rooms with people inside are warmer than empty ones.

4.2.5 Thermostatic control

The heating season is taken from 1st of October to 30th of April according to user schedule preferences. In the living room there is a temperature of 21°C while in the remaining zones, the temperature set point of the heating system is 18°C in accordance with the current Irish regulation (AECOM House, 2013).

During weekdays, occupants are usually at home before 9:00 am and after 5:00 pm while, during the weekends, occupants spend most of their time at home. According to which is the typical occupancy pattern between these two situations, the temperature is always maintained at the user set point.

4.2.6 Domestic hot water

The hot water tank has a storage volume of 0.278 m^3 and supplies the hydronic radiant heating system embedded in the building floor controlled by varying the hot and chilled water flow to the single unit. The water tank was modelled as water heater mixed, electricity fed and with 100°C of maximum temperature limit.

4.2.7 Weather and simulation period

Two design days have been considered in order to create the parameters for the program to generate the 24-hour weather profile that can be used for sizing as well as running to test the other simulation parameters. These days are 21st of February for wintertime and 21st of July for summertime and parameters include maximum dry bulb temperatures (-1.9°C and 22.1°C respectively), wind speeds (3.6 m/s and 4.8 m/s respectively) and solar radiation values calculated through ASHRAE Clear Sky Model (Powell, 1982).

Figure 4.10 shows graphically one of these features taken again from the International Weather for Energy Calculations (IWEC) data set.

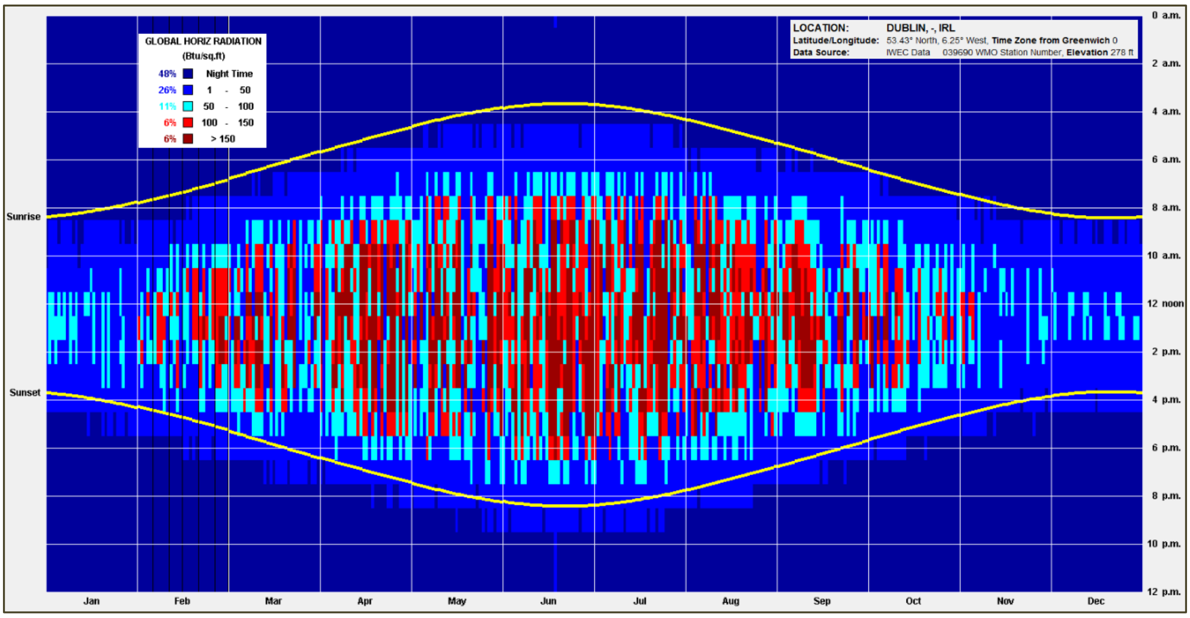

Figure 4.10. Global horizontal radiation for Dublin for 2014.

Source: IWEC

Moreover, some holidays/special days are set up to be used during weather file run periods such as NewYear's Day, St. Patrick's Day, Easter, Bank Holidays and Christmas.

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Chapter 5: Results and discussion

This chapter discusses the results from the EnergyPlus software analysis for both the heat pump and microCHP devices. The simulation results in two Excel tabs labelled one “Meter” and “Table”. In the first tab the information is one divided by the electricity consumption inside the building during the whole year among different items while in the second tab these data are given related to the features of the building. The analysis has been conducted using the values in kWh. The timeframes for analysis used were one week in wintertime and one week in summertime, respectively in January and in July, for both heat pump and microCHP in order to obtain the electricity profile of these two devices in two different conditions. The idea is to show the electricity consumption per day and to see if there is a trend or pattern to the data.

After that analysis, environmental and economic assessments have been carried out in order to produce a comparison between the technologies.

Additionally, a Net Present Cost (NPC) investigation has been implemented to get an observation among heat pump and microCHP devices in comparison with a conventional boiler (since that is one of the most mature technologies among building heating applications).

5.1 Electricity consumption for heat pump

Usually heat pumps present an electricity consumption graph where there are two main peaks, one in the morning when tenants do their activities before leaving the house and one during afternoon or evening when they return to home (Energy Sentry, 2013). This is more representative for a week day when people work, thus it is recommended to get two graphs, one for weekdays and one for weekend (Saturday and Sunday) to discover the main differences between them.

For the simulation we used the default heat pump device available in the EnergyPlus’s library already described in the previous chapter.

The weekday and weekend graphs are then used to compare simulation results with the real world situation for heat pump usage.

5.1.1 Wintertime for heat pump

Using a week in January from Monday the 16th to Sunday the 22nd and generating the electrical consumption of the residence for 24 hours in the software simulation. Using this information it is possible to graphically show how the electrical consumption varies during the day.

Firstly, we graph for a particular weekday (Wednesday the 18th) and then for a particular weekend day (Sunday the 22nd) of the same week created. Unfortunately, the graphs obtained for single days were meaningless particularly due to climate factors. To mitigate this we considered average results for weekdays taking values from Monday 16th to Friday 20th. Considering average values of weekdays obtained it is possible to produce the electrical profile consumption for the heat pump during this week as reported in Figure 5.1.

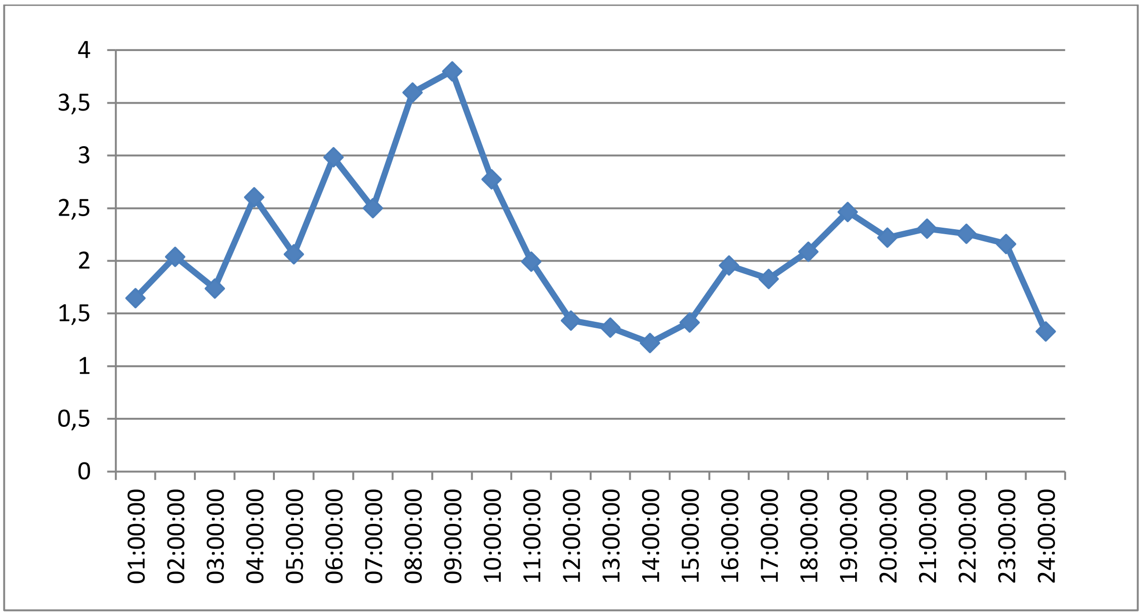

Figure 5.1. Weekdays electricity profile from Monday 16th to Friday 20th of January [kWh].

This graph shows clearly that there is a high peak in the morning hours, from 8:00 am to 10:00 am since people do their activities before leaving houses for the rest of the morning and lunchtime.

In fact, in the hours between midday and 3:00 pm one can see the lowest value of electrical consumption of the whole day as compared to night values. However, the value is over 1 kWh since there is still the need of space heating inside the house like night hours. Moreover, it is possible to notice another peak more or less at 7:00 pm due to tenants returning to the house and they get involved into different activities that require higher electricity consumption. In addition, to heating systems there are interior lighting, interior equipment and water systems.

Applying the same method to the weekend data in order to get a significant trend from it, we took an average value of electricity consumption for Saturday 21st and Sunday 22nd.
Taking the average value between these two days it is possible to get another graph that shows the electrical profile demands during a winter weekend as summarized in Figure 5.2.

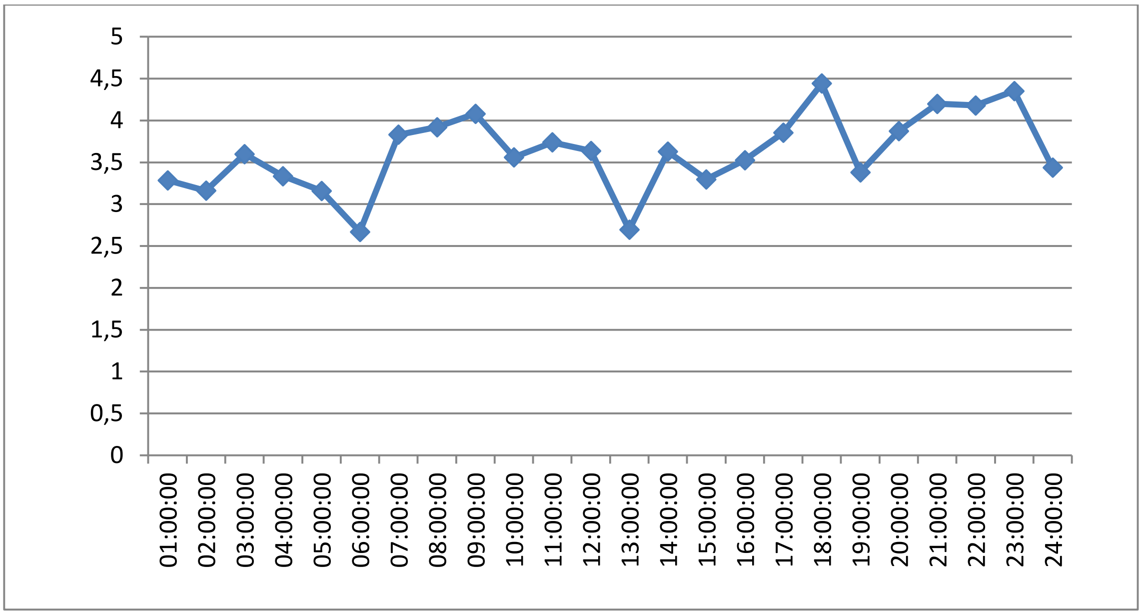

Figure 5.2. Weekend electricity profile for Saturday 21st and Sunday 22nd of January [kWh].

Here the situation is different from weekdays. In fact, during the weekend it is more likely that people are inside at home for more time than during weekdays so there is not the same variance of electricity consumption throughout the day. However, again in the hours of morning from 8:00 to 10:00 am and in the first hours of evening until 7:00 pm there are two main peaks for the same reasons that explained peaks of weekdays.
Additionally, the main differences between these two graphs are that during the weekend the electrical consumption is higher and more consistent as compared to the weekday.
During the week the average value is about **51.81** kWh, for the weekend average value it is approximately **86.83** kWh. Again, this contrast describes well the difference between the time occupation of the building during weekend days and during weekdays.

5.1.2 Summertime for heat pump

In the same way, it is possible to analyse the situation for the summertime period where we considered the week from Monday 10th of July to Sunday 16th of July.

Following the same approach used for the wintertime, we have divided results between weekdays and weekend days taking an average value for days from Monday to Friday and an average one for Saturday and Sunday.

In the first case, we got an average weekdays value for 24-day hours then taking it is possible to the electricity consumption profile as shown in Figure 5.3.

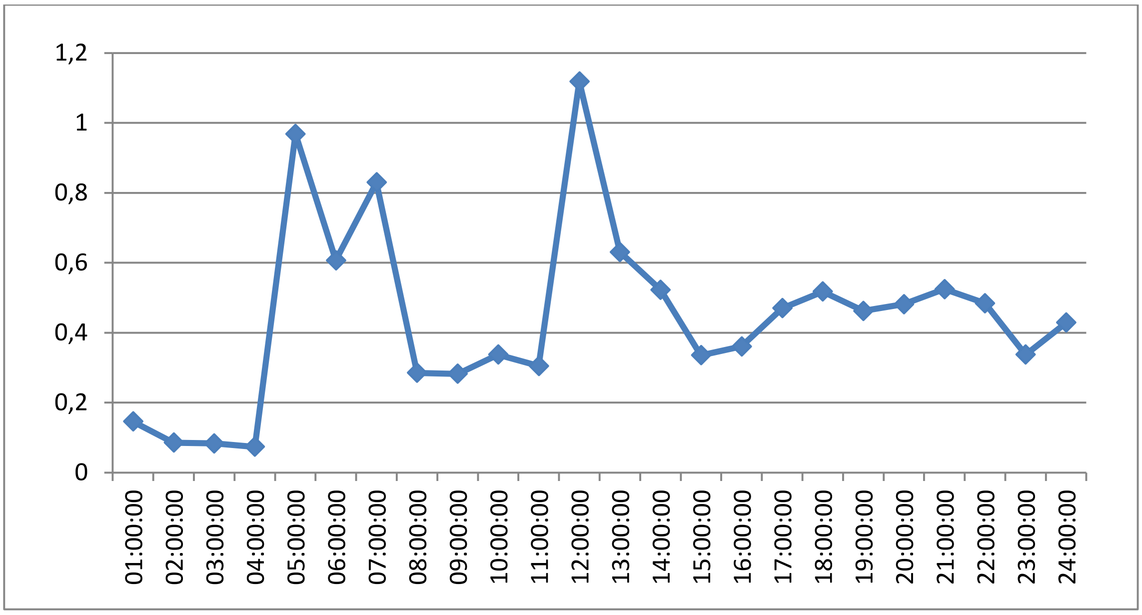

Figure 5.3. Weekdays electricity profile from Monday 10th to Friday 14th of July [kWh].

From this graph one can observe that there are two main peaks more evident than in wintertime weekdays electricity profile and with much lower value. In particular, the first one is again located in the morning from 5:00 am to 8:00 am while the second one is in the lunchtime between noon and 1:00 pm. For the rest of the morning and during the afternoon and evening the electrical consumption is fairly comparable and lower than wintertime. Furthermore, we recognize that during the night hours electricity consumption has almost a null value. This is the main difference to the wintertime profile due to the fact that in July electricity is not required to heat the house so the only demand is for appliances used and for domestic hot water.

Now we consider the weekend period with the average value between Saturday 15th and Sunday 16th. From this value derives the electricity consumption profile as reported in Figure 5.4.

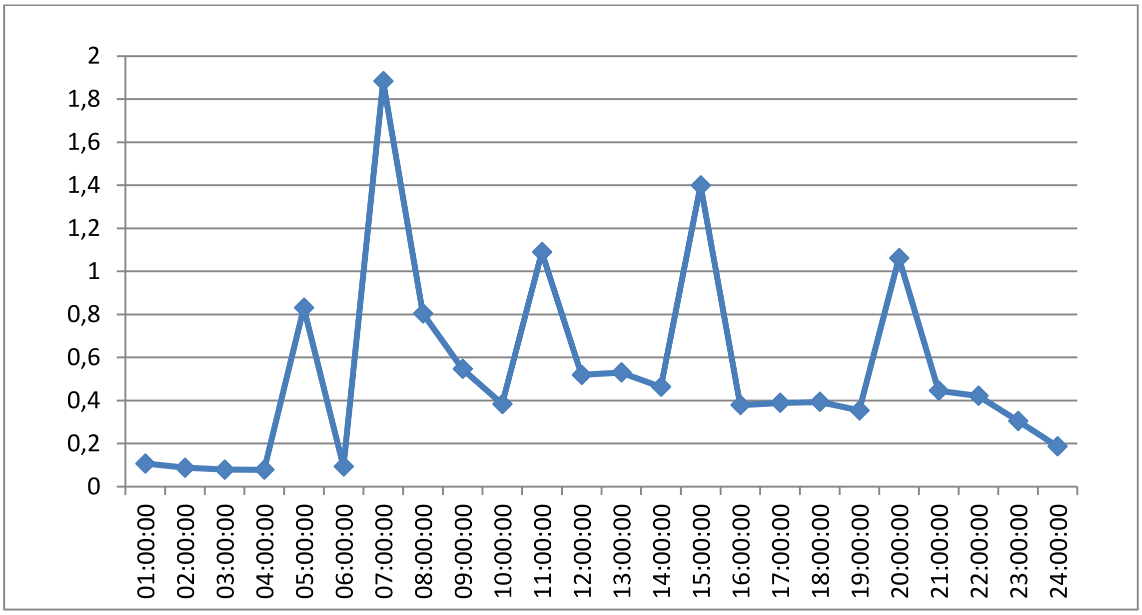

Figure 5.4. Weekend electricity profile for Saturday 15th and Sunday 16th of July [kWh].

In this situation there is still the main peak of electricity demand from 7:00 to 8:00 am and then there are some other high demands in particular during afternoon between 3:00 and 4:00 pm and in the evening during the dinner time from 7:00 to 9:00 pm. Similarly, to the weekdays graph one can see that during night time the electricity demand is almost zero. Conversely, the profile shows higher demand especially during afternoon and evening for the reason that inhabitants stay more time inside the house during the weekend than weekdays and this tendency is analogous to wintertime period.

Finally, if we take a look at the total amount of electricity consumption based on the average values in the two different week's period, this feature remains. For weekends there is a total amount approximately of **12.83** kWh that is slightly higher to **10.67** kWh that we get from the weekday period.

5.2 Electricity consumption for microCHP

Using EnergyPlus we created another simulation for the same building and with the same climatic data considering a microCHP device instead of a heat pump.

For the simulation we have used the default data for the natural gas fed microCHP given by the software library and already described in the previous chapter. For this case, the same analysis method for the heat pump simulation has been used. Therefore, we have considered the same two periods in wintertime and summertime.

It is essential to underline that while for the heat pump simulation we have used the **electricity consumption** within facility results present in “Meter” tabs, for the microCHP simulation, however, we need to study the **electricity net** results always taken from “Meter” tabs. This difference is due to the fact that the heat pump just requires electricity from the grid to make the compressor work while for microCHP we have to consider the electricity consumption by the building and the electricity produced by the device after burning natural gas. Specifically, if we take a look to “Meter” tab of microCHP simulation we can observe how the column of “Electricity:Facility” minus the column “ElectricityProduced:Facility” gives the result for “Electricity:Net” column.

5.2.1 Wintertime for microCHP

As for the heat pump model we have taken the week from Monday 16th to Sunday 22nd of January. In the same way we have considered an average value related to weekdays from Monday to Friday and an average from the weekend i.e. Saturday and Sunday.

So for the weekdays we have studied days included between Monday 16th and Friday 20th and the result is the average value of these days in the Excel file.

Taking these average values for each hour of a day we can create the following electricity profile as shown in Figure 5.5.

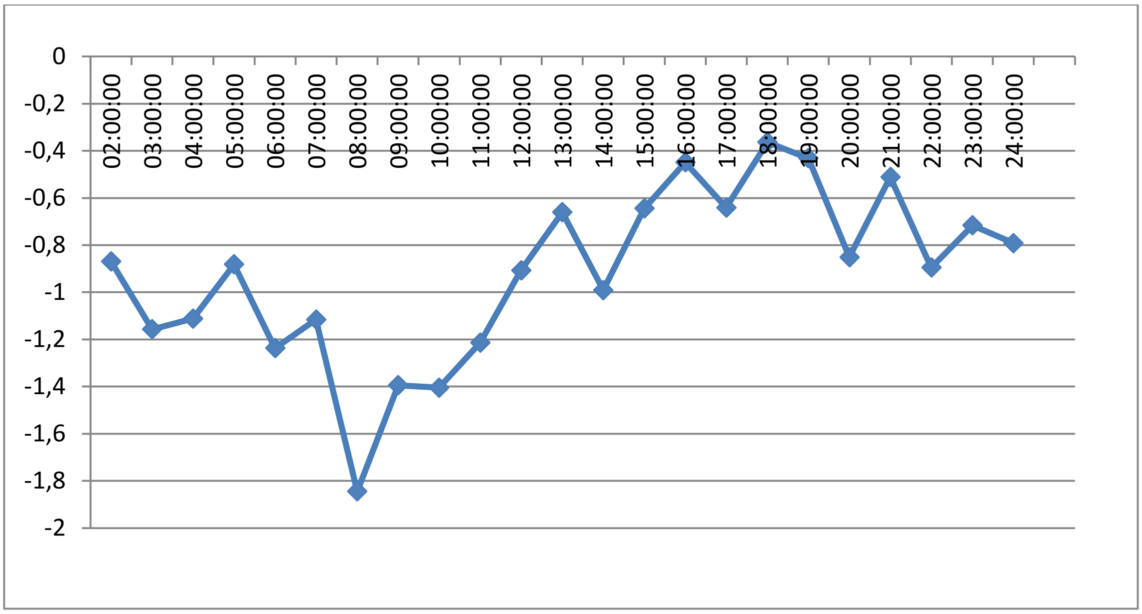

Figure 5.5. Weekdays electricity profile from Monday 16th and Friday 20th of January [kWh].

From this graph it is possible to notice how the electricity consumption stands for all hours in the day in values lower than zero which is quite different from the same graph for the heat pump. This situation is due to the fact that during wintertime the microCHP device generates electricity to produce domestic hot water and to satisfy the heating demand.

The main production of electricity is during hours from 7:30 am to 9:00 am where there is the most negative peak of the whole profile as for the heat pump. This is consistent with the earlier results, since the inhabitants are the same. The fact that the electricity profile has values lower than zero means that the microCHP device manages to meet the requirement of building for domestic hot water, heating and electricity consumptions such that no electricity from the grid is needed. After the average situation for weekdays it is possible to analyse the situation for weekends in the same way used for the heat pump approach considering the average value gained from Saturday 21st and Sunday 22nd of January. All these values are negative such as for the weekdays' situation and that means again that electricity from the grid is not needed. It is also possible to notice how the weekend's values are higher than weekdays' in absolute value. That is again since during weekend the building is occupied for more time by residents so demand for heating, domestic hot water and electricity is higher.

In fact if one compares the sum of two average values for weekend and weekdays in the whole 24 hours of the day, it is possible to find for the former a value of about **-61.25** kWh for the latter of approximately **-21.86** kWh. Considering average values the electricity profile for the weekend has been obtained as reported in Figure 5.6.

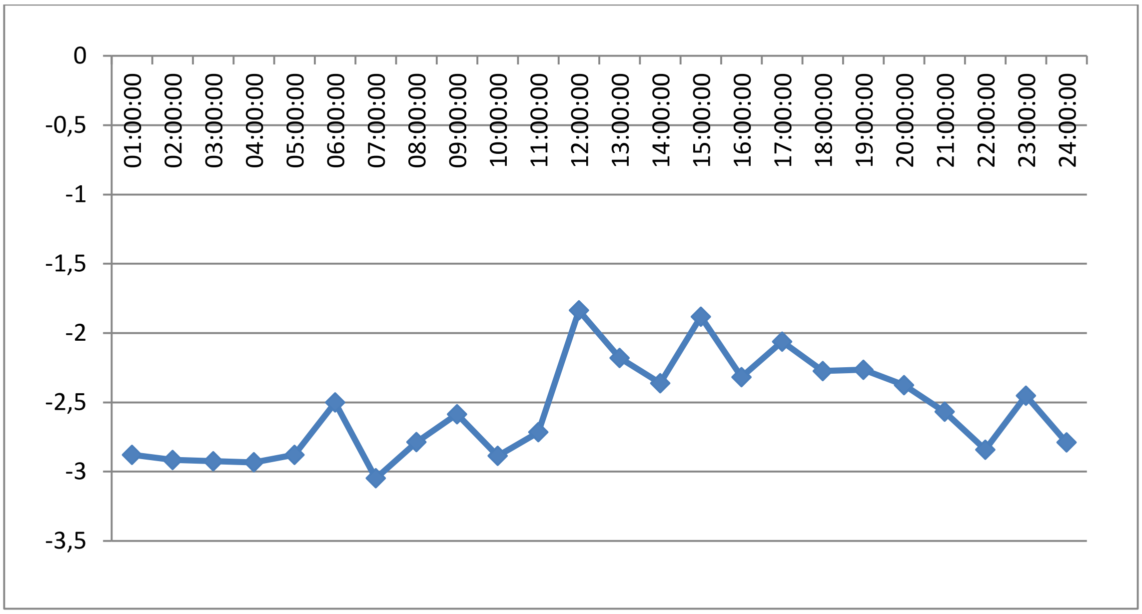

Figure 5.6. Weekend electricity profile for Saturday 21st and Sunday 22nd of January [kWh].

As already said for the heat pump case, compared with the situation of weekdays, during weekend the electrical consumption is more stable and the value of electricity net is higher as long as people stay inside the building for longer time.

There is not significant difference between night and day hours since the request of heating is always present over the day.

5.2.2 Summertime for microCHP

Equally to heat pump approach we have taken a summer week to analyse the results of simulation for the microCHP. Again the week investigated is the one from Monday 10th to Sunday 16th of July and it is divided between weekdays and weekend as well.

Considering weekdays the average value of days from Monday 10th to Friday 14th of July has been taken. Again, from it we get the graph of electricity consumption profile as reported in Figure 5.7.

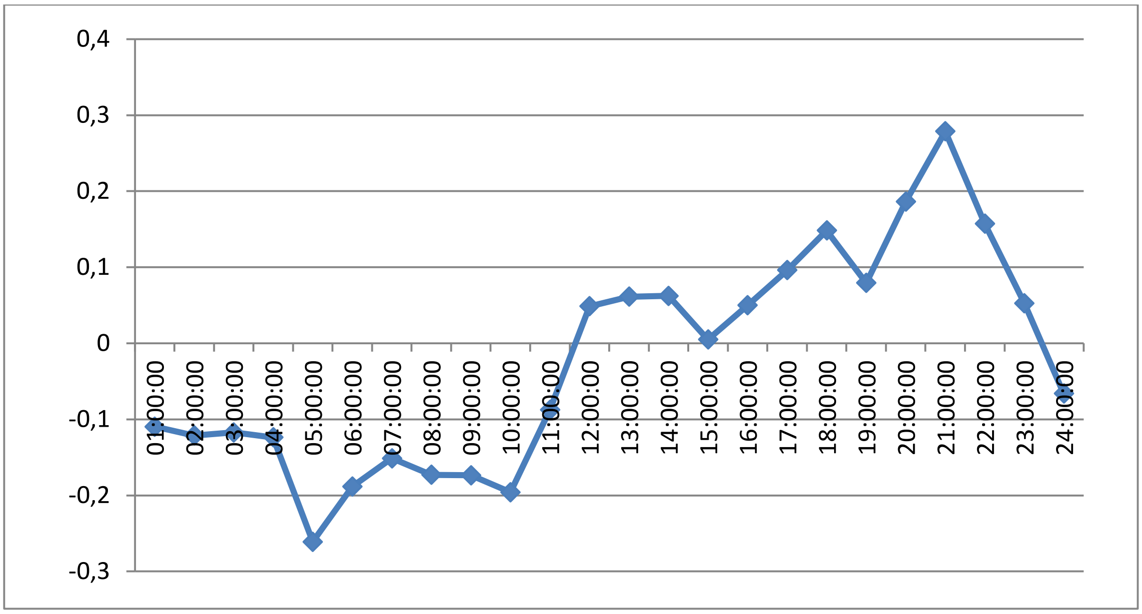

Figure 5.7. Weekdays electricity profile from Monday 10th to Friday 14th of July [kWh].

One can see how the summertime graph is different from the wintertime since in summertime the microCHP has just to work for producing domestic hot water and not to satisfy heating demand. In the morning hours between 5:00 to 7:00 am there is a negative peak due to demand of domestic hot water by the occupants, thus the electricity produced is higher than the demand and this creates larger negative (meter) values. After midday the electricity request is higher than production therefore the profile presents values higher than zero since the building takes electricity from the grid in the same way that the heat pump does in order to satisfy users' electricity request. In particular, there is a peak of the electricity consumption in the hours between 8:00 pm to 10:00 pm i.e. during and after dinnertime. Moreover, the electricity consumption during the night is close to zero value and this element is similar to the heat pump's summertime operation.

In the same way the situation for weekend has been considered always looking at the average value for Saturday 15th and Sunday 16th of July. From that it is possible to achieve another chart that illustrates the electricity profile for the weekend average value as exposed in Figure 5.8.

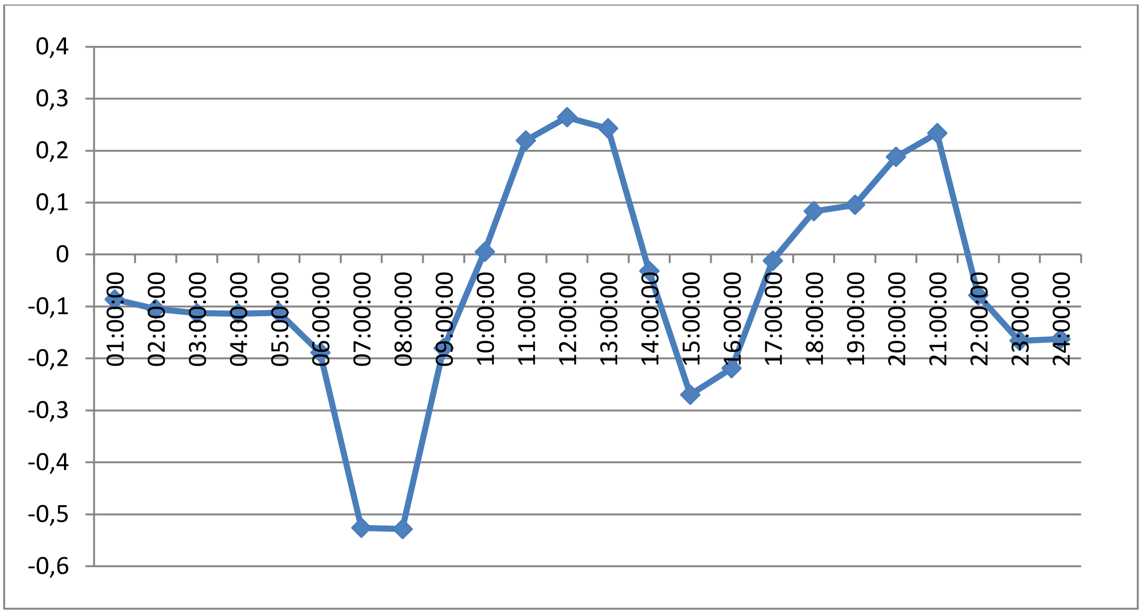

Figure 5.8. Weekend electricity profile for Saturday 15th and Sunday 16th of July [kWh].

This electricity profile has a similar trend compared with the weekday's one in particular there is the same peak in the morning hours between 6:00 am and 9:00 am with higher negative values of net electricity.

In addition, there are two positive peaks: first during lunchtime from 11:00 am to 1:00 pm which could be due to people eating at home and using the cooking equipment that requires higher electricity consumption. The second one during the evening time from 8:00 pm to 9:30 pm that is a similar situation compared with the weekday's graph since people are inside home during the evening.

5.3 Electricity consumption for end uses

The simulation results in the other tab in the output file called "Table" give information about electrical consumptions related to characteristics of the house.

The following pie chart in Figure 5.9 shows how the electricity consumption is divided among end uses over the whole year for the heat pump device.

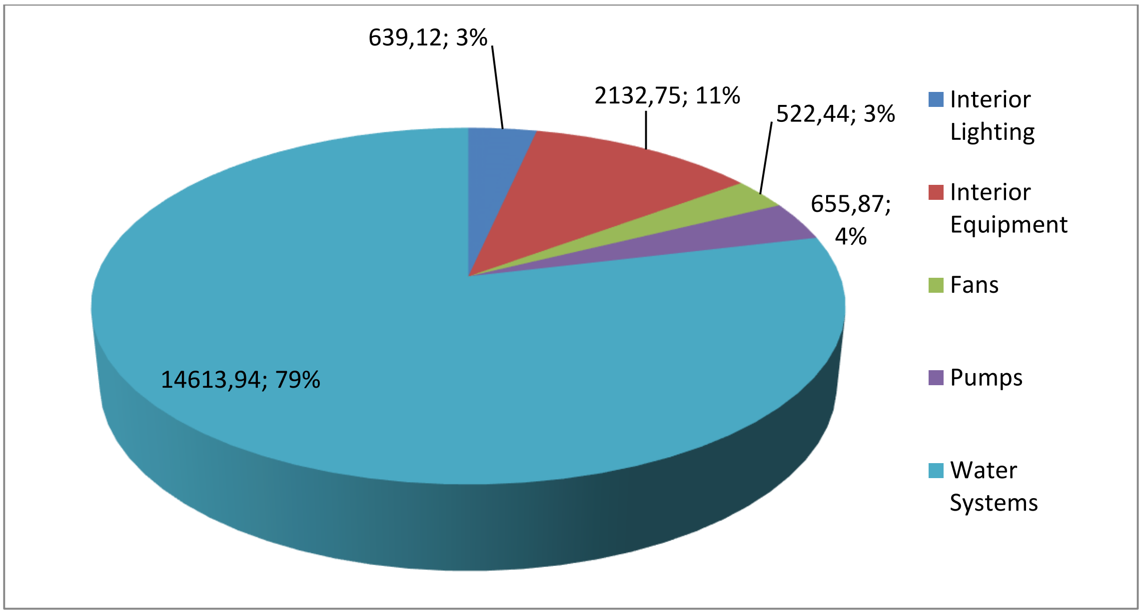

Figure 5.9. Percentages and values of electricity consumption by end uses for the heat pump in the whole year.

The total demand for interior lighting and interior equipment is clearly the same for both heat pump and microCHP and respectively **639.12** kWh and **2132.75** kWh.

The electricity consumption pie chart for the heat pump explains how electricity needed by the compressor to make the heat pump itself work is divided related to the users' requirement. The total electricity consumption for heat pump in the whole year is **18564.12** kWh.

The main entry of electrical consumption is water systems, the name that EnergyPlus uses to refer to the whole heat pump system. This item supplies both heating demand and domestic hot water. It has an absolute value of **14613.94** kWh with a percentage of 79%.

The balance of the consumption due to other systems has minimal affect except possibly the demand by interior equipment that presents a percentage of 11%.

From the same Excel tab called "Table" obtained from the software simulation for microCHP device it is possible to analyse the yearly electricity consumption by end uses as reported graphically in Figure 5.10.

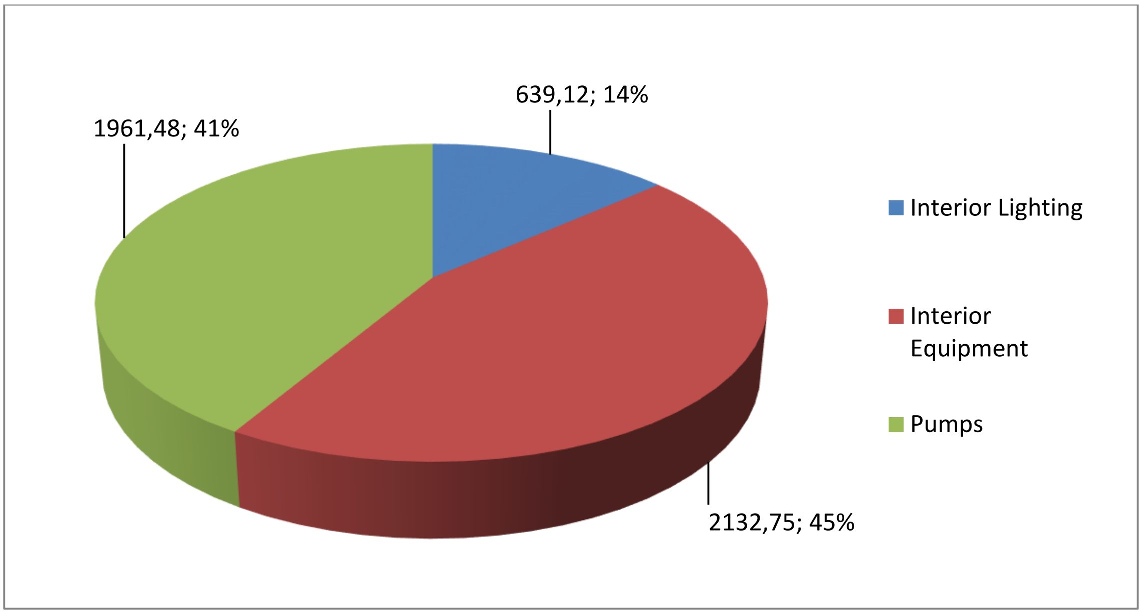

Figura 5.10. Percentages and values of electricity consumption by end uses for microCHP in the whole year.

The electricity consumption chart for the microCHP explains how the electricity produced by the device is used within the building to meet requirements.

For microCHP system there are three different items in which electricity consumption is divided. In proportion, the two main entries are interior equipment and pumps with a percentage respectively of 45% and 41%, while demand from interior lighting is much more limited. In the microCHP there is no requirement by water systems since heating demand and domestic hot water supply are satisfied by natural gas burning.

The total yearly electricity consumption for microCHP is **4733.39** kWh that is much lower than heat pump datum. This is because, for the heat pump one have electricity as input while for the microCHP one have to consider the natural gas that is used to feed the appliance.

5.4 Comparison between heat pump and microCHP

Since heat pump and microCHP devices work in different ways, they are evaluated with different parameters as already shown in the first part of this thesis.

Therefore, to decide which one of these two devices has the most optimized features for a given context one must follow an approach that normalizes the comparison since the parameters by which to assess each technology are different.

In particular, it is possible to have objective results about their performances following two different paths. The first one analyses the environmental performance of heat pump and microCHP while the second one studies the economic achievements of the two devices.

5.4.1 Environmental assessment

In order to classify environmental performances we look at two different ways for heat pump and microCHP depending on their structure.

However, the goal of this approach is to get the value of total production of CO_2 in the whole year that one must consider in the software simulation in order to see which one between these two appliances is more environmentally friendly.

5.4.1.1 Heat pump environmental assessment

For the heat pump analysis, it is possible to start from "Meter" tab results that is the electricity consumption for the whole facility for every day of the year.

These values are given for each hour of the day so for every day we consider twenty-four values. Starting from the 1st of January, which is a Sunday, we can obtain the global electricity consumption value for the whole year.

As already said before, this value amount to **18564.12** kWh.

After that, from the official site of the Irish electrical grid (Eirgrid Group, 2015), it is possible to gather values of CO_2 intensity grid for 2014 i.e. how much CO_2 is produced by the grid during the year while it is working, given in grams for kWh.

It is important to indicate that these values are given for every quarter of an hour and we use an average value for every hour in order to make it suit with the every hour value of electricity consumption given in the simulation's results.

Hence, for every single day of each month we collect 24 values of electricity consumption for the whole facility. The result is that we get a column referred to as CO_2 intensity of the Irish national grid that includes the same number of values of the first column made for the electricity consumption in the whole facility.

Now we have precise values of electricity consumption related to one precise value of CO_2 intensity for each hour of the whole year and then we multiply these values in order to get the production of CO_2 for heat pump per annum. The result is a value of **8535.74** kg.

5.4.1.2 MicroCHP environmental assessment

The approach that we used for the microCHP is different than the one used for heat pump since they work in a different way.

MicroCHP device considered for the simulation is an internal combustion engine fed by natural gas so, firstly, we check how much CO_2 is produced by burning this type of fuel.

Again, from “Meter” tab results purchased from EnergyPlus simulation, one can study the column of the gas consumption for the whole facility for each hour of every day of the year, considering values in kWh.

After that, we can take the value of carbon dioxide emitted by full combustion of each fuel, per unit of energy (Biomass Energy Centre, 2014). In particular, for natural gas this value is 227 g/kWh. Nevertheless, for the microCHP we must examine the electricity net related to the facility whence we have already the electricity profile for wintertime and summertime in the previous chapters. Using the column from “Meter” tab results with one value for each hour of the whole year. This parameter stands for the difference between the electricity demand required by the facility and the electricity production of the microCHP device.

Hence, in this column one can have some negative or positive values as already shown before. A negative electricity value in this column means that the microCHP manages to produce by itself the electricity needed by the tenants and they do not need to buy it from the grid.

Following, we will correlate to this column the same CO_2 intensity values that we considered for the heat pump case. Again, we took these values from the same source (Eirgrid Group, 2015) and we take an average value for each hour since they reported the CO_2 intensity for Irish electricity grid for every 15 minutes. As before, we took the same column of CO_2 intensity for the Irish national grid that we had used for the heat pump situation.

The difference for the microCHP appliance is that with negative values of the column we can consider the avoided emission of dioxide carbon from the grid since instead of importing electricity from the grid (with consequent production of CO_2) the microCHP device can supply on its own the building electricity demand.

In order to determinate the global yearly production of the microCHP it is possible to follow these steps: firstly, using the whole column of gas consumption in kWh and multiply each value for 227 g/kWh and we get the column of whole CO_2 production by burning gas. If we sum all values, we get approximately **13903.38** kg of carbon dioxide.

Secondly, for the column of electricity net for facility in kWh, one have to multiply each value of it for the correspondent one of the CO_2 intensity column given in grams of CO_2 per kWh that allows one to get the final column of dioxide carbon production for each hour of the year from the electricity consumption.

The sum of all these values is about **-4649.38** kWh. This negative value means that the electricity production within the microCHP device is considered as an avoided production of CO2 that we would not have had if we had bought electricity from the grid.

Next, we add 13903.38 and -4649.38 to have the result of roughly **9254** kg that is the whole year production of CO2 for the microCHP.

From this first criterion, it is possible to observe that heat pump is more environment-friendly since it has a lower CO2 production than the microCHP (8536 to 9254 kilograms in the year). It means that in the whole year the heat pump will emit about **718.26** kg of carbon dioxide less than if using the microCHP as shown graphically in Figure 5.11.

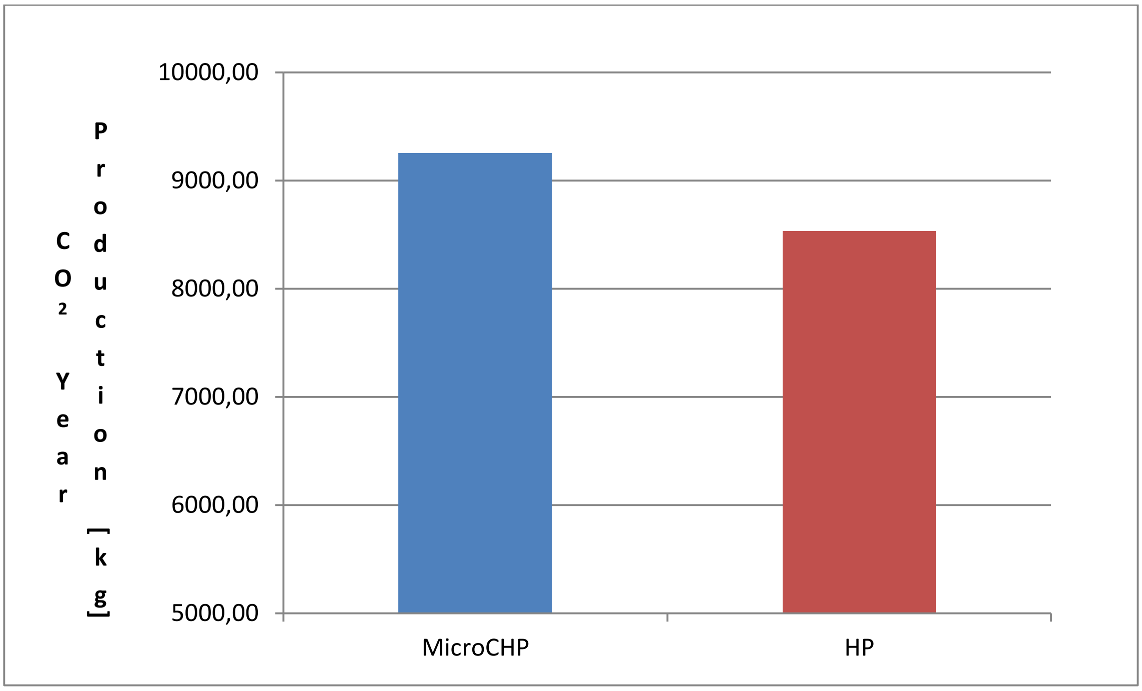

Figure 5.11. Whole year CO_2 production for microCHP and heat pump devices.

5.4.1.3 Monthly environmental assessment

It is also possible to analyse the trend of the production of CO2 for each month for both technologies as reported in Figure 5.12.

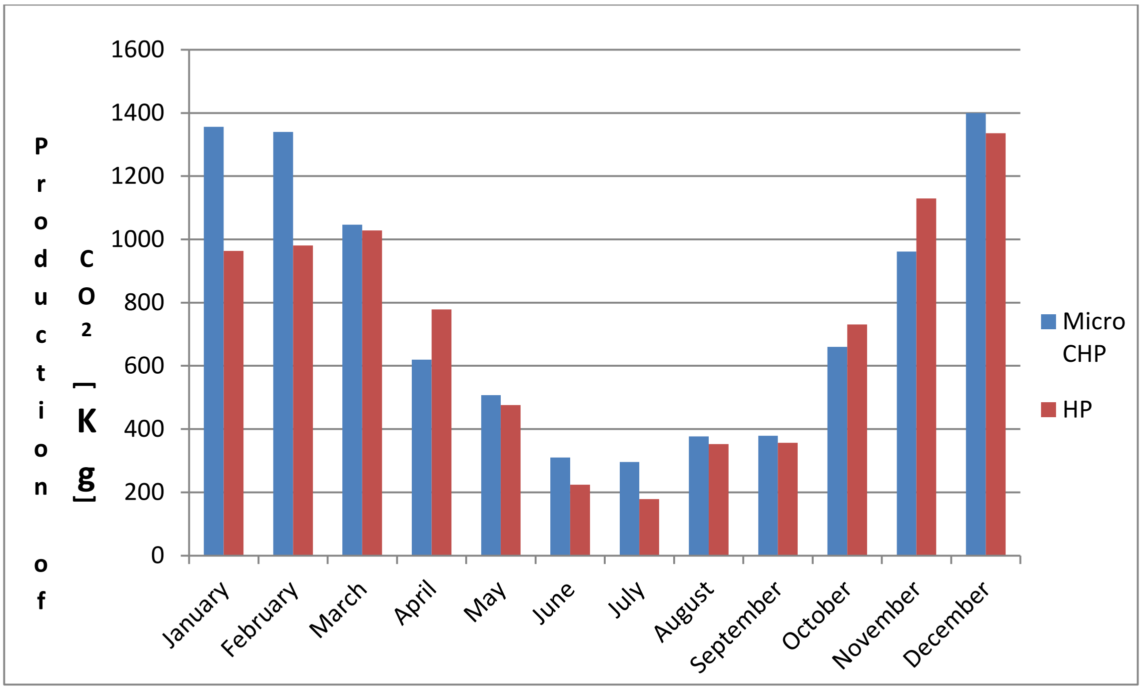

Figure 5.12. CO2 emissions for microCHP and heat pump devices for each month.

During wither months like December, January and February microCHP system has a higher production of CO2 compared to heat pump. The same situation is verifiable during summer months like June, July and August. Conversely, for some months during spring and autumn such as April, October and November the heat pump production of CO2 is slightly higher than for microCHP. Generally, this situation is explicable since in Ireland most of electricity is now produced by onshore (especially) and offshore wind farms built in the country. Therefore, in months where there is a higher production of CO2 by the heat pump means that wind blows less than in the rest of the year.

Less wind implies a higher production of carbon dioxide from the heat pump due to the fact that CO2 intensity of the national grid will be larger. Conversely, less wind will bring more CO2 production savings from the microCHP.

5.4.2 Economic assessment

The second way to compare heat pump and microCHP systems is through the economic criterion that specifies for which one of these two devices we will spend less money in order to supply users' requests. It is important to underline that, even if the software simulation refers to 2014 data, in this assessment current prices of electricity and gas have been considered for both technologies, as they did not vary geatly during these two years.

Moreover, it is important to say that this analysis does not take account of the investment costs of two technologies but only of the operating costs of them.

5.4.2.1 Heat pump economic assessment

As before, from "Meter" tab results we consider the electricity facility column that contains the values of electricity consumption for the whole building for each hour of the day. The analysis is always carried out considering values in kWh.

From the site of SEAI (Sustainable Energy Authority of Ireland), we can find the energy costs for different types of domestic fuels from 1st of January 2016 (SEAI, 2016).

What one must consider for the heat pump is naturally the cost of electricity and from this document it is possible to see how these costs vary depending from the band of the house that is the amount of electricity consumption per annum. As explained in Chapter 2, there are five different bands for electricity needs as reported:

- Band DA: <1000 kWh per annum;
- Band DB: >=1000<2500 kWh per annum;
- Band DC: >=2500<5000 kWh per annum;
- Band DD: >=5000<15000 kWh per annum;
- Band DE: >=15000 kWh per annum.

For each of these bands there is a different average price per unit given in €. So one needs to determine which of these bands applies to the building. To figure out that, one needs to find out the whole year electricity consumption for the heat pump and this value is easily findable making sum of all hourly data of the electricity facility column.

For this working problem, the annual usage is approximately **18564.14** kWh and following the guidelines above the building sits in band DE.

The average price per unit given for band DE is **0.17** €/kWh. By multiplying the annual electrical consumption for whole building for this tariff we can get the total price for the heat pump that amounts to roughly **3156** € per annum. This include just the operational cost of the appliance.

5.4.2.2 MicroCHP economic assessment

For the microCHP, as done for environmental approach, we re-consider the route to follow compared to the heat pump to accommodate for the different way of working between the two devices. Again, we must first consider the gas consumption for the whole facility taking the same column from "Meter" tab results with hourly consumption in kWh.
According to SEAI website, we could take the same document in order to see that, also for natural gas, there are different bands depending on the house yearly demand (SEAI, 2016). In particular, there are three different bands with different tariffs, as presented in Chapter 2. They are:

- Band D1: <5556 kWh per annum;
- Band D2: >=5556<55556 kWh per annum;
- Band D3: >=55556 kWh per annum.

Therefore, we consider how much the yearly gas consumption is for the whole building. This value is easily obtainable making the sum of each hourly value of the Excel column and it is about **61248.39** kWh.
Hence, the building belong to band D3 that has an average price per unit of **0.063** €/kWh. Multiplying 61248.39 kWh for 0.063 €/kWh, one picks up about **3858.65** € that represents the total money spent for providing natural gas. Subsequently, one must consider again the column of electricity net facility equally taken from "Meter" tab results in kWh.
We now consider the global annual value of electricity net facility that we obtain making the sum of all hourly values in the column. We get a value of **-10181.93** kWh that expresses the surplus that the microCHP produces and which could be sold to the grid. This is the main economic advantage of the microCHP.
Now, it is possible to assume just one value of the price for selling electricity produced by micro cogeneration even if it could vary during and year and even if in some periods we can have electricity bought from the grid because microCHP is not working or, if it works, it cannot supply the building demand.
Under this assumption, the price is fixed and one can find it in the website (Electric Ireland, 2016) where it is reported that the current average price per unit of electricity produced with microCHP device is **0.09** €/kWh and it will continue to be valid until 31st December 2016.

Afterwards, we can estimate the total revenue that residents could potentially receive by selling the electricity produced, by multiplying **-101821.93** kWh for **0.09** €/kWh which equals **-916.37** €.

If we subtract expense of the natural gas as fuel for the microCHP we determinate that the net cost of the microCHP is **2942.27** €.

In final analysis, we compare the total final prices of heat pump and microCHP that are **3156** € and **2942** € respectively. So the heat pump has an annual global cost that is roughly **200** € higher than the microCHP one as displayed in Figure 5.13.

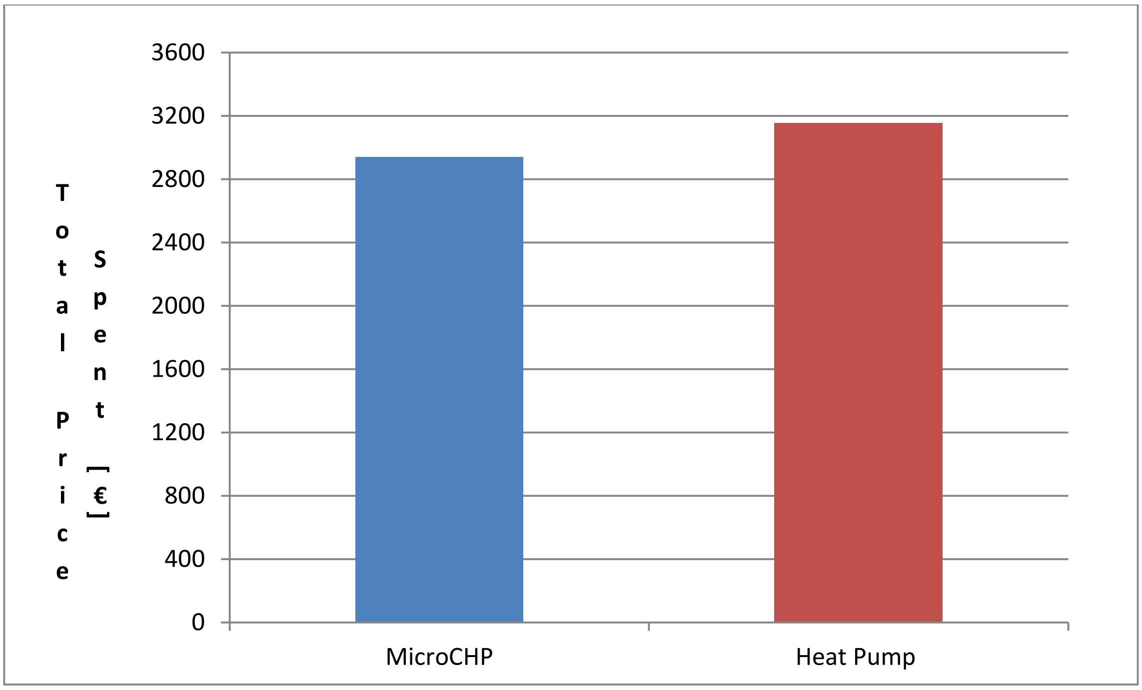

Figure 5.13. Yearly operational price spent for microCHP and heat pump.

5.4.2.3 Monthly economic assessment

As already done for the environmental criterion, it is possible to analyse how prices for microCHP and heat pump are split for each month as shown in Figure 5.14.

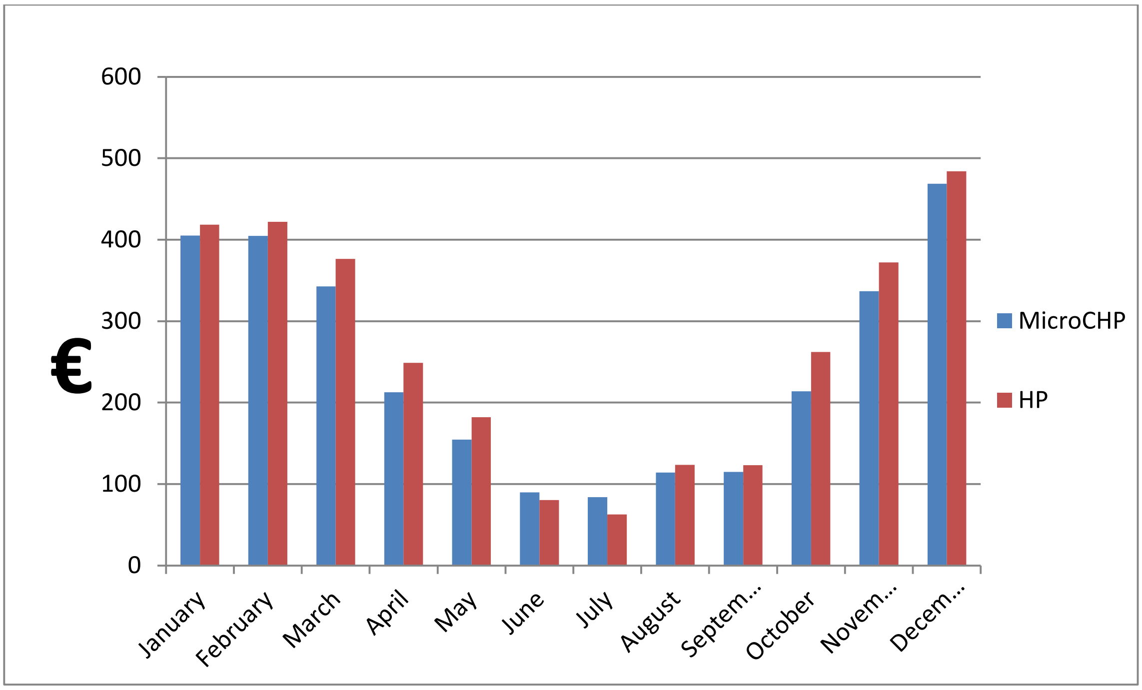

Figure 5.14 Overall operation cost for microCHP and heat pump devices for each month.

Except for June and July, where prices for microCHP are higher, for the rest of the year the total amount of the heat pump is higher. The reason for this trend is that, during June and July, the only request that heat pump has to supply is the domestic hot water since heating system in the house is not working. In the rest of the year, when also heating is demanded electricity bought from the grid by the heat pump is more expensive than the natural gas used to fed the internal combustion engine of microCHP device.

To sum up, using the results of these two approaches we can see that the heat pump is a better choice if the main concern is to optimise the environmental parameter since it emits a lower volume of CO_2. On the contrary, if money savings is the optimal parameter the microCHP is a better overall choice since annually it will cost less to operate than the heat pump.

5.5 Net present cost analysis

After the comparison between heat pump and microCHP, the aim of this chapter is to study these two technologies in relation to a mature heating device as a conventional boiler. In particular, this analysis is carried out following the method of net present cost (NPC) that actualize all revenue streams. Only cash flow spent are considered in a period of 20 years.

With this investigation, we want to see if a more eco-friendly appliance like heat pump or microCHP is more expensive, in terms of investment and operation costs, as compared to a conventional boiler. This study could be useful for a user that wants to submit his old heating boiler. In order to develop the analysis we use an Excel file where is reported Net Present Value (NPV) formula considering just the outgoing cash flows; in this case it represents the Net Present Cost (NPC). For all of three technologies assessment a discount rate of 5% has been taken and an annual rate of increase of energy price of 1% has been considered. Moreover, another assumption that has been made in this analysis is that the total consumption of electricity or gas do not change through 20 years therefore the same amount of revenue stream spent could be considered for each year.

5.5.1 Boiler simulation’s data

First, we need to have data about gas and electricity consumption of the boiler that we consider heating the house. It is possible to choose a conventional heating boiler from EnergyPlus default library that has a thermal output of 15 kW, an overall efficiency of 0.9 and that is fed by natural gas. Applying this data in the software with the same data used for previous simulations (climate data, building model, location, etc.) we can easily get another “Meter” tab results where are reported gas consumption and electricity consumption within the building for each hour of every day of the year. If we sum up these data, we obtain a yearly gas consumption of **37174.6** kWh and an electricity consumption of **3935.3** kWh per annum. An assumption made is that the price of electricity sold to the grid by microCHP device is constant during 20 years and it still amount to 0.09 €/kWh.

Applying the same method used before for the boiler, it is possible to notice how, with a gas consumption of 37174.6 kWh the house stays in band D2 while, with an electricity consumption of 3935.3 kWh the house stays in band DC. Since for band D2 the price is **0.067** €/kWh and for band DC the price is **0.24** €/kWh, we achieve a total amount for gas consumption of **2491** € per annum and a total amount for electricity consumption of **944.5** € per annum.

5.5.2 Analysis development

As already shown in the previous chapter, we have a total amount spent for electricity for the heat pump of **3156** € per annum while for microCHP we have a yearly amount spent for gas of **3858.65** € and an annual saving for electricity produced and sold to the grid of **-916.37** €.
In order to establish the NPC analysis, we have to consider the investment cost of these three technologies. This value will be the cash flow spent at the year zero.
Since the boiler is the more settled and spread technology for heating system its investment cost will be the lower. According to Vaillant website (Vaillant, 2015), it is possible to choose the model eco TEC Plus 615 that present a thermal output of 15 kW. The investment cost for this device is **1093** €. For the heat pump, according to www.climamarket.it/ (Carrier, 2015) website, it is possible to select an air to water heat pump with 15 kW of thermal output. The price for this appliance is **4048** €. Then, for microCHP device according to Senertec website (Senertec, 2015) and (Perdichizzi) we choose a Senertec (DACHS) model with 13 kW of thermal output, suited to request of the building. In this case, the investment cost consist of **13000** €. These three values represent the cost made at year 0 in order to buy these devices.
Now, we have to consider the total operation cost for each technology in 20 years.
Considering that the consumption of gas and electricity will remain the same for all 20 years and considering an annual rate of increase of energy price of 1% and a discount rate of 5%, using the Excel formula it is possible to evaluate the NPC for boiler, microCHP and heat pump.
From the assessment, it is possible to see that the NPC for these technologies are respectively: **45221.74** € for boiler, **44441.64** € for heat pump and **50228.16** € for microCHP. This situation is reported graphically in Figure 5.15.

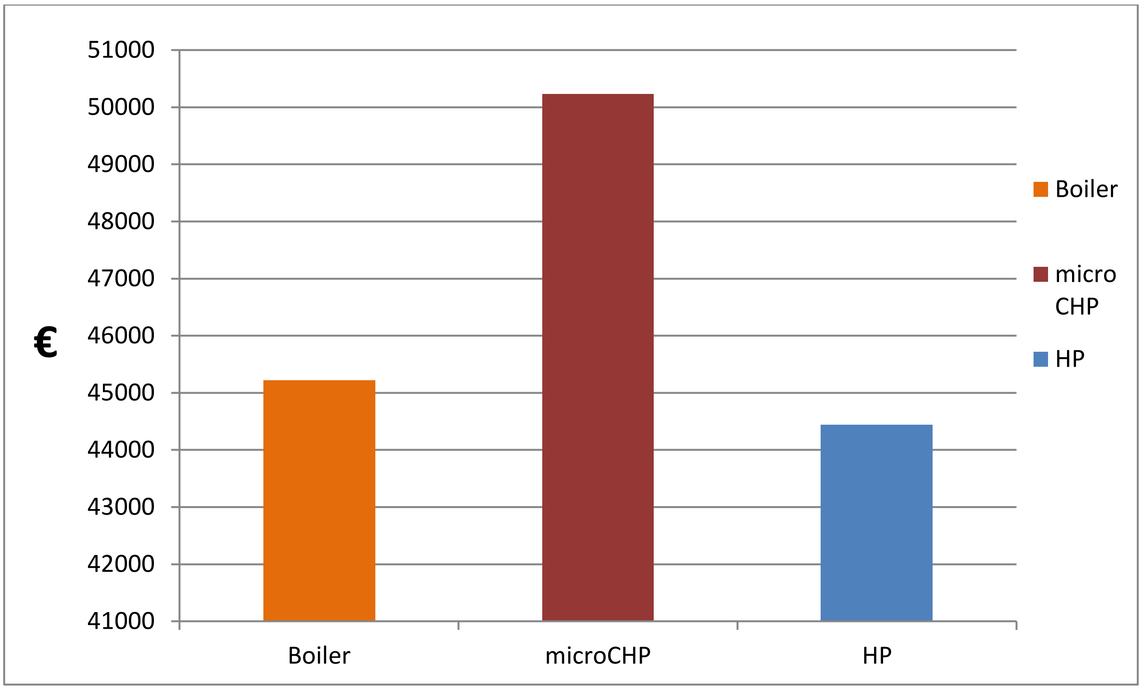

Figure 5.15. Comparison of actual values through NPC of boiler, microCHP and heat pump devices.

From this analysis, we can observe how the heat pump results as the better technology since it has the lowest actualized operational price. Moreover, in the previous chapter we have observed how it has also a lower production of CO_2 per annum compared with microCHP. If we have to replace an old boiler, a heat pump could be a good option even if its investment cost is much higher compared with the boiler.

This could be the same problem for the decision to install a microCHP since it has a high price of investment. Even if, as we assess in the previous subsection, it has a less operational costs compared to heat pump.

5.6 Considerations from the analysis

These technologies work well only if houses are energy-efficient, in particular they need to be well insulated. Related to building model used for the simulation, it is possible to think that with lower U-values, higher performances of energy savings would have been reached. Generally, the advantage in cost savings would be more significant when heat pumps and microCHP are integrated with passive building concepts of air tightness and low-temperature heating design.

Major barriers for both heat pumps and microCHP include the high initial cost and insufficient recognition of benefits. First, consumers could help the penetration of these technologies inside the market if they are sensitive to the protection of the environment since much less CO_2 production is obtained respect to conventional technologies. Moreover, it is important that policy measures are present to promote the use of technologies including the standardisation of efficiency indexes, system labelling and incentives in the form of subsides and grant. For both technologies, the high investment cost, compared with conventional technologies, is often recognized as disadvantage, even if the overall operation cost under life-cycle approach is lower. Therefore, incentive schemes could be useful tools to encourage the whole value chain including, among others, certified/qualified installers and end-users that can be stimulated to make this significant investment. In the absence of financial supports, the significant investment cost for end-users is extremely difficult to overcome. They could be institutional schemes facilitating or providing infrastructure or financial schemes through special tariffs, grants, taxed based incentives or feed-in-tariff. These schemes must be transparent, accessible and comprehensible, with defined timelines and amounts (Carbon Trust, 2011). Grant schemes have been effective in promoting of both microCHP and heat pumps and in helping to overcome the initial capital cost barrier.

Heat pumps depend mainly on grid features. Its action is carbon free and the building’s CO_2 footprint is contingent on the electrical supply from the grid. Heat pumps could not only reduce the use of fossil fuel and related CO_2 emissions with the substitution of conventional heating systems but they also enable an energy switch from conventional fossil fuels to electricity, the production of which is (increasingly) based on significant share of renewable energy in many countries. For the case of Ireland, where lot of electricity is produced by wind this technology is attractive if renewable energies are fostered. If feed-in-tariff were presented for electricity produced by renewable source, heat pumps could be more attractive. This could also help to overcome high upfront investment costs for the consumer point of view.

For microCHP the main benefit is the construction of distributed generation that could transform consumers into “prosumers” (product-consumers) giving them greater control over their energy use and production and become active participants in the energy system, to cut their carbon footprint. Hence, behaviour and mentality of the users could help the spread of this technology. Moreover, regarding to an internal combustion engine microCHP, a lowering price of gas could increase the savings but a consumer could not rely on this since it is really fluctuant.

What could really foster a microCHP penetration in the market are transparent and stable feed-in-tariff about generated and exported electricity by this device.
Feed-in-tariff scheme is useful for micro cogeneration diffusion since the scheme guarantees to pay a fixed tariff for each kWh of electricity generated, and an additional payment for each kWh of electricity exported to the grid (SEAI, 2011). It is designed to increase the number of installations of micro cogeneration technologies and to reduce the payback time of the investment. In Ireland this scheme is present just for biomass and anaerobic digestion CHP plants.

Currently, in Ireland, do not exist dedicated government policies for the promotion of heat pumps and microCHP even if they really would help. For example, the UK has recently developed a policy and grant-aid programme that have the goal to increase heat-pump penetration in the residential market. Furthermore, in the UK also exist defined, stable feed-in-tariff mechanisms for microCHP since the UK green energy cashback generation tariff offers a 10 p/kWh generated electricity plus 3 p/kWh exported electricity (Carbon Trust, 2011). These example represent the importance of central Government interventions since the UK, as Germany, are the countries with larger numbers of these devices installed in proportion to end-users in Europe.
As for the Italian context, there are regulatory laws and financial incentives for both heat pumps and microCHP appliances. For heat pumps, heating and cooling are required due to prevailing Mediterranean climate of the country. Therefore, heat pumps are considered to play an increasingly important role, as they can be used for both heating and cooling. Regarding microCHP devices, several forecast thinking that could supplant conventional boilers. However, for both technologies the problems are always high upfront costs, lack of awareness of their benefits, high payback periods and lack of well-informed installers. Consequently, similar to Italy, with weak governmental action towards the implementation of these technologies, their penetration, especially in the residential sector, will be very hard.

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Chapter 6: Conclusions

The aim main of this thesis work was developing a comparison between a heat pump and a microCHP device in the heating of a detached house located in Ireland. This analysis has been carried out following environmental and economic criteria.
The secondary objective of the work was providing an overall view on the state of art of these two technologies, on the business models suitable for them and on currently regulatory framework at European and Irish state level that could foster their penetration in the energy market.

Regarding the literature review, treated in the first part of this work, main parameters and typical values of the two technologies have been defined. For heat pumps we have Coefficient of Performance (COP) and Seasonal Performance Factors (SPF) while for microCHP devices we have defined thermal, electrical and overall efficiencies, Primary Energy Savings (PES) and Carbon Benefit Ratio (CBR). In order to define these parameters two field trials lead by the Energy Saving Trust (for heat pumps) and the Sustainable Energy Authority of Ireland (for microCHP) have been followed. Moreover, a brief overview of various types of heat pumps and microCHP devices was presented.
Regarding business models, ESCOs, leasing and feed-in-tariff models were discussed. Implementations of these models, based on local or regional contexts, could help the penetration of heat pumps and microCHP devices into several energy sectors, including residential heating market.
Finally, a discussion on regulatory frameworks showed that there are specific European Directives that regulate microCHP and renewable sources (including heat pumps) market, define the operation of these appliances and explain how each Member State must transpose them into a national legislative framework. The discussion paid particular attention to Ireland since the simulation and modelling work is set around a residential building in Ireland.

The technology comparison discussion focused on an air to water heat pump and an internal combustion engine microCHP. To perform the comparison the following were necessary: create a model of the residential building to be used in the simulation, design the heating plant

layout and specify the single hour operational settings during the year chosen for the simulation, 2014 in the case. The software used for the simulation was EnergyPlus.
From the results of the simulation it has been possible to observe the electricity profile of the two technologies during the summertime and the wintertime and, comparing them, it is possible to understand when there is an electrical or, a thermal demand. This has been the first way to compare the performance of each technology. Moreover, from the results of the simulation, according to the electricity consumption of the heat pump and the gas consumption and electricity produced by microCHP it is possible to obtain how much CO_2 they produce in the whole year. Taking the value of the CO_2 intensity of the national Irish grid we assess a yearly CO_2 production from the heat pump of **8535.74** kg and from the microCHP of **9254** kg. From the same data, we determine the price of electricity and gas according to the building yearly consumption, and it is possible to evaluate the yearly operation cost of the heat pump that is **3156** € and the operation cost of microCHP which amounts to **2942** €. According to these results, the heat pump is more attractive from an environmentally friendly point of view since it produces roughly **700** kg of carbon dioxide less than the microCHP in the whole year during its operation. Conversely, microCHP has a lower cost of operation since the annual operating cost of the heat pump is about **200** € higher, without considering the initial investment cost.

Additionally, a Net Present Cost (NPC) analysis, developed for 20 years, has been carried out in order to compare these two appliances and with a conventional heating boiler. We use the same data resulting from the software simulation.
With an investment cost of **1093** € for the boiler, **4048** € for the heat pump and **13000** € for the microCHP the NPV study gives the following results: an actual value of **45221.74** € for the boiler, **44441.64** € for the heat pump and **50228.16** € for the microCHP.

Due to the technological differences between the air source heat pump and the gas-fuelled microCHP, we use a variety of criteria to normalize those differences. This allows us to observe the optimal nature of each technology within a given context. Operationally, the heat pump returns the better results as it has the lowest actualized operational price and it has also a lower production of CO_2 compared with microCHP. Both these technologies have a much lower operational cost compared with a conventional boiler and their main barrier to uptake inside the energy residential market is their high initial investment cost.

Market uptake barriers and alternatives for consumers were discussed. The reality is that the market needs to be prepared in order to foster the penetration of these systems. There needs to be (at a minimum) a sufficient amount of qualified installers, certified equipment available and ready to install and educated consumers. It is also important to recognize the role of the Government in terms of market uptake and providing support through clearly defined regulatory frameworks. In addition, approachable business models for investment in renewable energy and energy efficiency (such as heat pumps and microCHP) could help private consumers to make such purchases. By clearly stating the benefits of long-term investments and addressing concerns such as the high up-front costs, the business models can mitigate a lack of awareness and knowledge about these technologies. In particular, ESCO's scheme or financial institutions such as banks can promote the uptake of heat pumps and microCHP with creation of leasing or loan schemes. The large-scale deployment of heat pumps and microCHP is affected by factors that are common to other emerging technologies such as uncertainties in the market and the long-term nature of investment in the energy sector. Therefore, in order to achieve their full potential, investments in infrastructure are needed, along with supportive business initiatives and an increased social awareness of environmental issues.

In the end, the results from the analysis and the literature review show that heat pumps and microCHP systems in the residential heating context are feasible projects, attracting both economic and environmental aspects. Generally, to become economically desirable the investment cost must be lower or, at least, the end-user must have the possibility to overcome this barrier with fostering business models. It is furthermore fundamental the development of relevant policies and regulations that include stable grant schemes, feed-in tariff schemes in order to define and stimulate benefits of these technologies.