

DANIEL JAKOB

HYBRID HEAT PUMP ANALYSIS

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THE OPTIMISATION OF A HEAT PUMP–GAS BOILER COMBINATION IN A
RESIDENTIAL HOME

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CONTENTS

I Preamble

1	Introduction	3
1.1	Context	3
1.2	Aim	7
1.3	Motivation	8
1.4	The Problem	8
1.5	Thesis Layout	8
2	Literature Review	9
2.1	Heat Pumps	9
2.1.1	Vapour-Compression Cycle	11
2.1.2	Hybrid Heating Systems	11
2.1.3	Buffer Tank	13
2.1.4	Frosting and Defrosting	14
2.2	Heating Degree Days and Design Temperatures	16
2.3	Primary Energy	20
2.4	Electrification of Heating	21
2.5	Controller and Control Theory	22
2.5.1	Noise and Error	23

II Model and Results

3	Methodology	27
4	Model	29
5	Sensitivity Analysis	31
6	Techno-Economic Assessment	33
7	Conclusions	35

	Bibliography	37
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iii Appendix

A Appendix Test 45

A.1 Appendix Section Test 45

A.2 Another Appendix Section Test 46

LIST OF FIGURES

Figure 2.1	HHS with an AWHP and condensing gas boiler [11]	13
Figure 2.2	Heating Duration Curve	19
Figure 2.3	PE breakdown by fuel type and sector	21

LIST OF TABLES

Table A.1	Autem usu id	45
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LISTINGS

Listing A.1	A floating example (listings manual)	46
-------------	--------------------------------------	----

ACRONYMS

COP Coefficient of performance

HHS	Hybrid heating system
ASHP	Air source heat pump
PE	Primary energy
PEF	Primary energy factor
PES	Primary energy savings
SPF	Seasonal performance factor
SCOP	Seasonal coefficient of performance
RHI	Renewable Heat Incentive
AWHP	Air-Water Heat Pump
HP	Heat Pump
HHPS	Hybrid Heat Pump System
RES	Renewable Energy Share
HDD	Heating degree days
PID	Proportional-integral-derivative

ABSTRACT

Short summary of the contents in English... a great guide by Kent Beck how to write good abstracts can be found here:

<https://plg.uwaterloo.ca/~migod/research/beck00PSLA.html>

Keywords: Hybrid heat pumps.

DECLARATION

I hereby certify that the submitted work is my own work, was completed while registered as a candidate for the degree stated on the Title Page, and I have not obtained a degree elsewhere on the basis of the research presented in this submitted work.

Belfield, Dublin 4, May 2023

Daniel Jakob

ACKNOWLEDGMENTS

Put your acknowledgments here.

Dedicated to...

NOMENCLATURE

Physics Constants

c	Speed of light in a vacuum	$299\,792\,458\,\text{m s}^{-1}$
G	Gravitational constant	$6.674\,30\times 10^{-11}\,\text{m}^3\,\text{kg}^{-1}\,\text{s}^{-2}$
h	Planck constant	$6.626\,070\,15\times 10^{-34}\,\text{J Hz}^{-1}$

Number Sets

\mathbb{C}	Complex numbers
\mathbb{H}	Quaternions
\mathbb{R}	Real numbers

Other Symbols

ρ	Friction index
V	Constant volume

Part I

PREAMBLE

INTRODUCTION

1.1 CONTEXT

In Europe in 2022, the residential sector was responsible for 27% of final energy consumption [13] Domestic water heating and space heating collectively account for close to 80% of a household's energy usage. [14]

Climate change has also directly affected heating and cooling design. ASHRAE highlight that for 1274 weather stations/observing sites worldwide with sound data between 1974 and 2006, the averaged design conditions (which are explained in [Sec. 2.2](#)) over all locations had changed by the following:

- the

The so-called *electrification of heat* has been supported in the EU for some time now due to seeking carbon emissions reductions and also security of supply, which has indeed become more of an issue than previously thought...Electric heating devices such as Heat Pumps (HPs) convert electricity into heat, creating the sought after link between building heating and the electrical grid [15]. However, this link will not come without growing pains, as more buildings rely on the electrical grid to provide electricity for heating, the electrical demand grows. Due to the nature of heating demand and weather/climate which generally affects large areas and subsequently a large number of houses simultaneously, the electrical grid would be of course put under large strain when a particularly cold spell of weather hits an

area. These great peaks in energy demand are a problem when it comes to electrical grid deployment, as the real-time balancing of the grid becomes an increasingly difficult job with the large variability of renewable energy production methods such as wind. [29, 30] propose that Hybrid heating systems (HHSs) could alleviate these very high energy demands from heating systems, could they manage to intelligently switch to primarily gas operation during peak energy demand periods.

In Ireland, the housing stock increased by just 0.4% between 2011 to 2016 [21]. Very few new houses are being constructed with the possibility for newer, more efficient space heating and/or hot water production systems and better, holistic insulation. A similar sentiment has been noted in other Western European countries, making this not a localised issue, but rather an international one [11, 17]. Thus, in order to reduce Primary energy (PE) consumption in any meaningful way, retrofits must be carried out on existing buildings. This includes adding insulation to attic spaces and/or walls of the house and the installation of more efficient heating systems. An advantage of HHSs is that existing buildings presumably already have a heat generator, be it a gas boiler or otherwise, which can be easily integrated into a HHS with the addition of a HP. Of course, plumbing works must be carried out and the HP itself has a relatively high barrier to entry in the form of a high upfront cost. Currently the Ireland do not give grants for the installation of HPs as they do not deem them to be a renewable type of heat generator. This is partly true as HPs do use electricity to run.

The transfer of heat from a low temperature region to high temperature region is not something that would happen through normal thermodynamic means, as heat can be thought of as flowing in the direction of decreasing temperature, when a temperature differential exists, of course. Rather, special devices called refrigerators can be used to achieve this. HPs (for heating

purposes) and refrigerators are identical in architecture, differing only in objective. Refrigerators aim to cool an enclosed volume of air, typically a refrigerator or freezer, while a HP aims to heat an enclosed region, namely a residential home, in the case of this project. Refrigerators work utilising the refrigeration cycle, with the vapour-compression refrigeration cycle being the most commonly used cycle for refrigerators, HPs and air conditioners. The reversed Carnot cycle is the most efficient form of a refrigeration cycle, and is only an idealised theoretical model, not practically achievable. HPs and air conditioners are composed of the same mechanical components [7], meaning one single system can be used for the cooling and heating of a home. This is achieved by adding a reversing valve to the hydronic circuit.

The performance of Air source heat pumps (ASHPs), or HPs in general, is very different to that of a traditional gas condensing boiler. The performance of a HP is almost entirely determined by the outdoor temperature and climatic conditions. The performance of a HP is described by the Coefficient of performance (COP) of the unit. This measure varies throughout a heating season, day and even from minute to minute. A HP with a COP of 3 for example, produces three units of heat energy for every unit of electricity supplied. This *extra* energy is being gathered from a renewable energy source — which in the case of Air-Water Heat Pumps (AWHPs) is the external air. The amount of non-renewable energy consumed by HP at any given time depends on the Renewable Energy Share (RES) of the grid. According to Ireland, Ireland's RES for electricity is around 9.3%. This figure is expected to increase in the coming years/decades as more wind turbines are installed, other renewable energy generators are built, the Celtic Interconnector subsea line between Ireland and France, and multiple non-renewable energy plants are de-commissioned.

Since the [COP](#) of a [ASHP](#) varies quite drastically over a heating season, the measure Seasonal coefficient of performance ([SCOP](#)) is often used to describe the performance of a [HP](#) over a year or a heating season.

[HPs](#) have over recent years become more popular throughout Europe

There are three main types of [HPs](#) for space heating (i.e., not air-conditioning): [AWHPs](#), Ground-Water Heat Pumps and Hydro-Water Heat Pumps. Ground-Water [HPs](#) acquire their heat energy by exploiting the heat contained within the Earth's soil. Soil, below a certain depth has a very consistent heat, only fluctuating mildly seasonally. The added benefit of this type is that soil below a certain depth will not freeze, which would cause frosting like in [AWHPs](#). Hydro-Water [HPs](#) gain their heat from water sources such as ponds, lakes or well-water. The temperature of water fluctuates far less than the ambient air temperature, meaning they do not extract as much energy as [AWHPs](#) on warmer days, however, during warmer days, the heating load of a residential home is much less than the peak load. Conversely, during very cold days, the water remains much warmer than the air, which is very beneficial during those high-load spells. These two types of [HPs](#), due to their heat sources, have their merits, however, it is also due to their heat sources that they are relatively obscure and not commonplace. Installing these types of [HPs](#) is costly, complicated, time consuming and require permits to build. Due to these reasons, [AWHPs](#) are the most common form of [HP](#) sold in Europe [1].

Frosting is detrimental to the performance of [HPs](#). During cold, humid weather, frost builds up on the evaporator coils on the outdoor component of the [HP](#). Frosting dramatically lowers the heat conductivity between the coils and the ambient air, being essentially insulated by the frost. Frosting is a major concern in cool, humid climates, Ireland being one such climate.

A Hybrid Heat Pump System (HHPS) as opposed to monovalent systems, is a configuration of a HP in combination with a conventional gas boiler. During warmer days, the HP has sufficient heating capacity to provide all the energy needed to heat a space, while being very efficient, while on colder days, it may be not economical or ecological to run the HP. During these periods, the majority of the heating load is passed to the gas boiler, which is not affected by the ambient air temperature. A control system can be put in place to intelligently turn on and off the HP and gas boiler to better suit the current weather, for either economical or ecological reasons, or a weighted combination of the two. A (INSERT NAME FOR IT HERE) system is where the predefined external temperatures for turning on/off the HP/boiler are not coincident. This creates a temperature range wherein the HP and boiler are running simultaneously. This is the focus of this thesis: where lies the optimal crossover points for boiler-only operation, bivalent operation and HP-only operation, specifically for the Irish climate. This research has been carried out for other climate types. The Irish climate is unique in that the temperature range (during the heating season) is quite narrow, the humidity is quite high almost all year round (especially on the west coast) and the temperature is quite quite mild.

1.2 AIM

The aim of this thesis is to first, give an overview of the current state of research regarding HPs and explain their operation including advantages, disadvantages, principle of operation and use cases.

1.3 MOTIVATION

The operation, control and performance of [HHSs](#) consisting of [AWHPs](#) and traditional gas boilers has been moderately studied in the literature. This type of heating system has been simulated and testing in-situ in countries such as China, Japan, Germany and other continental European countries, however, the research regarding efficient control of such a system in the Irish climate, namely a temperate oceanic climate, has not (or at the least only partially) been explored. Ireland has a very changeable and mild climate, but the characteristic of note is its consistently high humidity. Humidity and low temperatures are the bane of [HP](#) operation and efficiency.

1.4 THE PROBLEM

1.5 THESIS LAYOUT

[Chap. 2](#) is a literature review of: the operation of [HPs](#) (including the different types) and [HHSs](#); overview of [PE](#); the electrification of heating in the EU; controllers and basic control theory; and ending with

LITERATURE REVIEW

2.1 HEAT PUMPS

HPs work by harnessing the energy from low temperature sources such as air, water or the ground. HPs of any kind acquire energy from its surrounding environment in the form of low-temperature heat and *concentrate* it to heat comparatively minute volumes to its surroundings. This is achieved through a vapour compression cycle, explained in Subsec. 2.1.1. Under ideal conditions, AWHPs have extremely high COPs in the 3.5 to 4.5 range. This is of course from their ability to harvest the aerothermal energy from the outside air. The main downfall of AWHPs is that when the external air temperature is low, their COP is reduced significantly. Due to this inherent disadvantage, HPs are essentially unfit to be the sole space heating generator for almost all applications, depending on climates and design points. While HPs have the capacity to perform heating and cooling, this thesis and associated simulations do not consider the cooling of a building or home, and therefore is only concerned with heating and considers only the heating-season timeframe of the year. The space-heating radiators found in existing homes are not suitable for cooling [17], the cold water in the radiators does not cool the room effectively and condensation on the radiator surface may become an issue.

Because the efficiency of HPs is so dependent on the outside air temperature, the measure of Seasonal performance factor (SPF) is typically used to characterise them when considering the

performance over a certain heating period. The [SPF](#) represents the ratio of the total useful energy produced by the [HP](#) during a heating season, to the seasonal electricity consumption. For example, an [SPF](#) of 3 would mean that over a given year, the [HP](#) produced 3 units of heating energy for every unit of electrical energy provided. Due to [HPs](#) extracting renewable energy from the surrounding air, the [SPF](#) is (or should be) always higher than 1, and generally is above 3. EU legislation states that in order to be eligible for the Renewable Heat Incentive ([RHI](#)), a [HPs](#) [SPF](#) must be above 2.5 [9]. [17] investigated the efficiency gains from the implementation of a [HHS](#) in a retrofitted house built in the 1970s. They compared this to other monovalent heating systems. A medium sized heat pump was used.

[HPs](#) come in many different heat capacities, from single kilowatt units to extremely large units which can heat large multi storey office buildings. In residential home contexts, the largest [HPs](#) generally available are almost 300 kW. If an [ASHP](#) were to be sized so large as to have the capacity to provide the entire heating envelope of a residential home during even the coldest expected temperatures, the [ASHP](#) would (aside from being prohibitively expensive), be so oversized that when temperatures are moderate, the [HP](#) would produce so much heat as to heat the space so quickly that it would have an extremely short on-off cycle [4]. Since the peak load for heating occurs for a very small number of hours during any given heating period, this would be very detrimental to the unit, specifically the condenser component. The frequent on-off cycling significantly reduces the longevity of the condenser, and would require replacement long before what would be expected. Many manufacturers suggest that the number of on-off cycles should not exceed 6 per hour. To avoid this issue, [AWHPs](#) are specifically undersized. Various “design temperatures” can be calculated for a given location. For Dublin, the design temperature which covers 99.0% of the

annual heating is -0.7°C . **AWHPs** are usually sized to meet a design temperature of 60%–70%, as opposed to more traditional space heaters, as is further explained in [Sec. 2.2](#).

HPs tend to perform better when providing space heating through underfloor heating. This is partly due to underfloor heating being more efficient in general than other, more traditional space heating methods, namely hot-water radiators. Another reason more applicable to **HPs** is that the (space heating) inlet water temperature for underfloor heating is much lower than radiators. This means the **HP** does not have to heat the circulating water as hot as it would with radiators. The temperature delta between water temperature inlet to the **HP** and the outlet is simply lower and therefore less energy has to be produced by the **HP** in the first place. However, retrofitting houses with underfloor heating is expensive and very intrusive to the building — as obviously (all) floors much be ripped up and coils must be placed and plumbed — which discourages many homeowners from performing this type of retrofit.

2.1.1 *Vapour-Compression Cycle*

2.1.2 *Hybrid Heating Systems*

A bivalent, hybrid **HP** heating system consists of a **HP** of some description and an auxiliary or supplemental heating source [5]. The **HP** type this thesis focuses on is a **AWHP**, and the auxiliary heating source is a conventional condensing gas boiler. The overarching idea behind this dual heating source system for a home is: the (undersized) **HP** can provide heating to the home using electricity, rather than gas, as its energy input during milder periods of the heating season with minimal usage of the gas boiler, and during the more severe, colder periods of the season, the gas boiler can provide the majority of the heat required to

keep the home at a comfortable temperature. [AWHP](#) performance is very weather dependent, as explained in [Sec. 2.1](#), and during very cold, humid spells simply cannot provide enough heating capacity to maintain a comfortable temperature inside, unless it is wholly oversized, which has problems associated with it, described [Sec. 2.1](#). Therefore, almost all of the literature agrees that an undersized [HP](#) with a “correctly” sized gas boiler is the most efficient system [[3](#), [11](#), [23](#), [24](#)]. [Fig. 2.1](#) shows a schematic diagram of a [HHS](#) comprising of an [AWHP](#), gas boiler, buffer tank, radiators, sensors, and controller. The blue line represents the “cold” water, which has just expelled its heat to the indoor rooms and is circulating back to the [HP](#) and gas boiler to be heated up again. This return water is typically in the range of 25 °C to 30 °C by the time it reaches the heating devices. The heating devices heat the water up a temperature in the range of 45 °C to 40 °C, where makes its way back to radiators to once again expel its stored heat to the indoor rooms, which for a comfortable temperature, are in the neighbourhood of 18 °C to 22 °C.

The controller of this system determines how much heat is being added to the circulating water by the two heating devices, the sum and also the share. During milder days, it is understandable that a lower quantity of heat is required to maintain the home at a comfortable temperature, while during colder days, more heating input is required. The [AWHP](#) can only run at full tilt, however, ideally, the controller can control the circulating water flowrate in such a way as *step down* the heat output of the [AWHP](#)/gas boiler to create the ideal heat flux from the radiators into the air of the rooms to maintain a nice indoor temperature. The controller

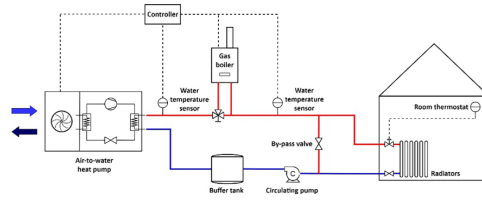


Figure 2.1: HHS with an AWHP and condensing gas boiler [11]

2.1.3 Buffer Tank

A buffer tank is a medium- to large-sized water vessel used in hydronic heating systems. It provides a large thermal inertia to the heating system-house system, which many small- to medium-sized houses, especially those with poor insulation, lack. Thermal inertia is a desired property of a building as rapid thermal fluctuations in ambient air are less of a concern when it comes to maintaining a comfortable thermal environment indoors. This effect is noticeable in large office/district buildings with high thermal inertias and plays a significant role in heating-capacity selection [22]. Furthermore, a buffer tank provides a “hydraulic switch” and allows for heat generation and heat distribution to be in separate loops. This opens up the option to have differing flowrates between the heat generation and heat distribution loops.

Buffer tanks have been found, when sized correctly and with an appropriate control strategy, to have a positive influence on the efficiency and performance on HHSs [17, 25]. The controller is able to make use of the HPs “most profitable working conditions” thanks to the presence of the buffer [10]. It has been found that when a buffer tank is present in the HP circuit, SPF increases as the size of the HP decreases [20]. Mugnini et al. confirmed this for all sizes of HPs simulated, the smallest buffer tank having a capacity of 200 L.

The larger a buffer tank in volume, the larger its energy storage capacity. However, with a larger volume, and naturally larger cylinder and surface area, comes greater heat loss, which seem to correlate almost linearly [17]. This could be justified if other performance factors such as SPF or load factor were positively affected to offset this loss in heat, however this does not seem to be the case according to [25] and Klein, Huchtemann and Müller, which also found only a moderate reduction in on-off cycles with smaller tanks. This is partly to do with the thermal inertia of the building and return temperature controller. Klein, Huchtemann and Müller found that the volume of the buffer tank had very limited effect on the system performance. Dongellini, Naldi and Morini sized their buffer tank just large enough such that the maximum number of on-off cycles was never greater than six per hour, resulting in a buffer tank with a volume of 79 L. This maximum on-off cycle figure was chosen based off their HP manufacturer guidelines. Daiken suggest [10]

2.1.4 *Frosting and Defrosting*

Frosting occurs in ASHPs in colder ambient temperatures resulting in issues for HPs. Frost build up depends on the ambient temperature, temperature of the surface in question and relative humidity. For heat pumps, a few ranges of temperatures at which frosting occurs has been found in the literature [26] finding a range of -15°C to 6°C at a r.h. of ≈ 90 , while [18] found frost formation to begin when the ambient air temperature was below 3.5°C with a r.h. of 88%. Frosting specifically occurs when the surface temperature of the fins on the air-side heat exchanger component (evaporator) are lower than the dew point of the of the air. Water droplets start to form and collect on the fins. When the temperatures is below freezing or close to it, the water droplets freeze to the fins and build up a frosting. Frost, unlike snow, which both form from the freezing of water droplets, is

not loose and must be scraped off or melted off. It will not *fall off* of a surface like snow might. This layer of frost acts as a layer of insulation and restricts the heat exchanger from transferring heat from the ambient air. Since these fins are typically closely packed, if the layering of frost continues and progressively builds up, the airflow around the fins decreases and so does convective heat transfer to the ambient air, further exacerbating the issue of insulation. All of this is to say that when frosting occurs in ASHPs, their performance declines severely. [31] found that the temperature of the air and surface of the fins, humidity, velocity of air are the main factors involved in frost formation.

Many treatments for frosting have been proposed and implemented into products. There is however no golden bullet solution, all of their advantages and disadvantages. Three main solutions are typically used when addressing the issue of frosting in ASHPs.

- Simple on-off defrosting: the HP is simply switched off when too much frost has formed on the outdoor component. The performance has been degraded to such a point that it is now economically advantageous to turn off the HP and wait for the frost to melt away. This however, takes a long time and can negatively affect the thermal comfort of a home if no other heat production is used. The HP does not use any power during this off-cycle of course, retaining the COP of the HP— although, this may affect the overall system performance if a gas boiler needs to be used to provide the entire heating load of the home.
- Reverse cycle defrosting: this method is similar to the first method; the refrigerant is cycled in reverse and hot gas is forced into the heat exchanger. Recall that HPs and refrigerators differ only in objective. The HP now treats the outdoors as the “cold” sink and begins transferring heat from indoors to outdoors. Intuitively, one can see that this is quite detrimental to the performance of the HP as the

house is being actively cooled in order to heat up the outdoor coils and fins to melt away the frost, and one cannot forget water's high thermal capacity... The intention in this method is to melt the frost much quicker than the first method, allowing the ASHP to begin warming the home once again much earlier than the simple on-off defrosting method.

- Resistive heating: electric resistive heaters are installed on/in the heat exchanger. This method works very well, quickly melting off frost and is a separate heating element to the HP and therefore does not interrupt the HP's cycles. Resistive heaters are very expensive to run and negatively affect the COP of the HP.

[2] found that the reverse cycling method resulted in a higher COP than the other two methods.

2.2 HEATING DEGREE DAYS AND DESIGN TEMPERATURES

Heating degree days (HDDs) is a measure of the difference between the outside temperature and the inside temperature. HDDs are usually considered over a period of time, be it a month, heating season or entire year. A *base* temperature is chosen, typically around 12 °C to 21 °C which then determines when it is "cold" outside, or can be thought of as being the temperature above which heating is no longer considered to require heating. This base temperature can be chosen at will, and simply depends on what the person/institution deems to be *warm enough*. This measure can be used to quantitatively compare the heating demand of a given house in different locations/climates. The heating requirement of a specific building are directly proportional to the HDD [6].

To calculate the [HDD](#) for a certain day, three equations are used and are displayed from [Eq. 2.1](#). Which equation to use is determined by the interaction between the base temperature and the maximum temperature recorded during that day.

$$\text{Degree days} = \begin{cases} t_{\text{base}} - \frac{1}{2}(t_{\text{max}} + t_{\text{min}}), & \text{if } t_{\text{max}} < t_{\text{base}} \\ \frac{1}{2}(t_{\text{base}} - t_{\text{min}}) - \frac{1}{4}(t_{\text{max}} - t_{\text{base}}), & \text{if } t_{\text{base}} > \frac{1}{2}(t_{\text{max}} + t_{\text{min}}) \\ \frac{1}{4}(t_{\text{base}} - t_{\text{min}}), & \text{if } t_{\text{base}} < \frac{1}{2}(t_{\text{max}} + t_{\text{min}}) \end{cases} \quad (2.1)$$

To calculate the Monthly degree days however, only ?? is made use of. This total is found by summing the daily temperatures differences and can be seen in [Eq. 2.2](#).

$$\text{Monthly degree days} = \sum_{\text{month}} \left[t_{\text{base}} - \frac{1}{2}(t_{\text{max}} + t_{\text{min}}) \right] \quad (2.2)$$

Environmental Design: CIBSE Guide A. has chosen a base temperature of 15.5 °C. *2009 ASHRAE Handbook: Fundamentals* used a base temperature of 18.3 °C and determined an annual [HDD](#) of 3135 °C d for Dublin Airport, IE, N53°26' W6°15'. Using the online tool [Degree Days.Net](#) [28] with a base temperature of 15.5 °C, a [HDD](#) figure of 2072.3 °C d was obtained for the same location.

Design temperatures are a measure how many hours/days a specified condition is exceeded. In the case of a heating design temperature, this would indicate how many days of the year or heating season are spent below a given temperature. *2009 ASHRAE Handbook: Fundamentals* notes that this measure does not give an indication of the frequency or duration of these events, only a cumulative result is returned. According to *2009*

ASHRAE Handbook: Fundamentals, the 99.6% design temperature in Dublin Airport is -1.9°C while the 99.0% design temperature is -0.7°C . Traditionally, conventional gas boilers or resistive heaters were sized to design temperatures, meaning, for a chosen design temperature percentile (e.g., 99.0%), the heater could heat the building to thermally comfortable levels for 99% of the year, however during the 1% temperature lows, the heater would not be adequate. This calculates to the heater being undersized for ~ 35 hours of the year.

$$\begin{aligned} 365 \times 24 &= \\ 8860 \text{ h} &\Rightarrow \\ 99.0\text{-ile} &= \\ 8760(100 - \\ 99.0) &= 87.6 \end{aligned}$$

In monovalent systems, the HP is sized in such a way as to be able to provided the entire heating load for a building at design conditions. This results in the HP being positively over-dimensioned for the task [17].

The concept of a *design-day* can be used to design heating configurations for homes, especially when performing numerical simulations on a model of the system [24]. A design-day file is a special weather file created with design conditions in mind. Based on the design temperature parameter, ASHRAE lays out a procedure to generate a 24-hour weather profile. These profiles represent the 0.4% to 99.6% extremes experienced for a particular location. This weather data is used in simulations to determine the minimum size for a heater required for a house (for these particular percentiles of course).

for the purposes of
the simulation(s)
concerning this
thesis, the 0.4
percentile, and
any
cooling-nessecary-
temperatures for
that matter, are
not of concern as
cooling is out of
scope.

The “heating duration curve” can be devised for a specific climate and a specific HP where a curve is plotted on a chart with heating load [kW h^{-1}] against number of hours the heating load is equal to or above a selected percentage of design load. For example, as illustrated in Fig. 2.2, the blue line indicates 50% design load, and lands around 1300 hours on the x -axis. This means that for 1300 hours of the year/heating season, the heating load of the building is 50% of the design (or max) load. The balance point marked by the yellow circle is the point at which the HP is not longer able to provide the entire heating load re-

quired by the building. To the left of this point, the gas boiler will need to provide the remaining heat capacity to maintain a comfortable indoor temperature. If the [AWHP](#) size is increased, this balance point moves to the left, as the [HP](#) can provide the entire heating envelope of the building at lower temperatures. Of course, for the sake of the diagram, the curves and lines in this figure are arbitrary (e.g., [AWHP](#) performance is not linear with outdoor temperature, and by proxy, heating load), but it illustrates how a [HP](#) may be sized to 60% of the design load of a building.

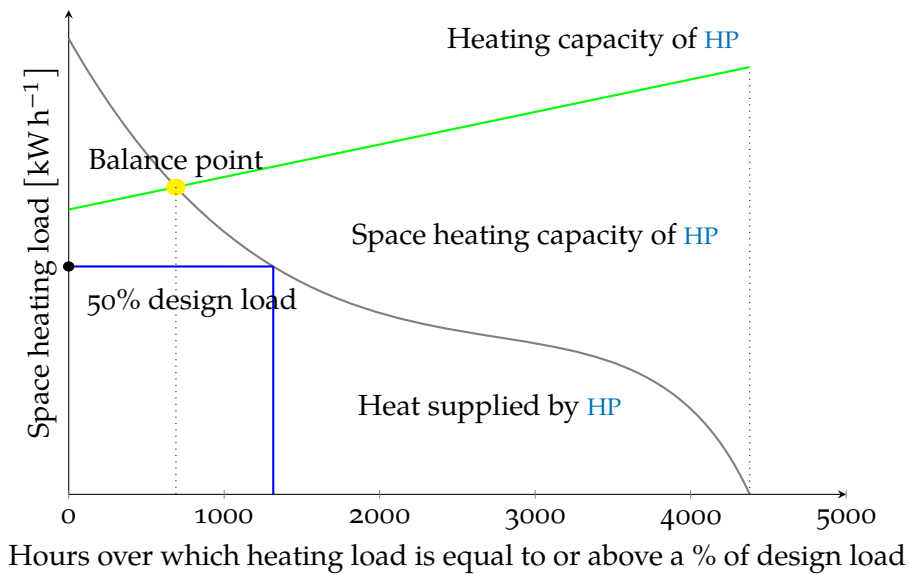


Figure 2.2: Heating Duration Curve

All of this is to say that there are many methods of determining and comparing the heating load of a building for a given climate, with which heating devices may be sized to in order to be able to (almost always) have the capacity to heat a building. A [HHS](#) is unique in that it is composed of two heating devices. The boiler, as stated before, is sized to a certain high-percentage design condition. This may be defined by the user/homeowner,

convention, or by some set of standards set by a governing body (e.g., ASHRAE), and is typically a value in the region of 95% to 99.7%. On account of this, the [AWHP](#) can be sized smaller than compared to if it were the sole heating device.

2.3 PRIMARY ENERGY

[PE](#) is a term used in the fields of energy statistics and energetics. Sources of [PE](#) are those which have not been interfered with by humans, in other words, are the natural form of energy and are unprocessed. [PE](#) sources include: oil, natural gas, sunlight, wind, etc. [PE](#) stands in contrast to secondary energy, which can be thought of as the carrier of energy, which most commonly happens to be electricity, but can also be liquid forms of energy (e.g., diesel/petrol,), hydrogen fuel cells or (waste) heat. Following from [PE](#), is Primary energy factor ([PEF](#)) which connects [PE](#) to final energy, it is a measure of how much energy in total is required to produce a unit of *usable* energy. [Fig. 2.3](#) is a sankey diagram which breaks down the flow of energy in Ireland in 2020 from [PE](#) on the left by fuel type, and final energy on the left, by sector. It also highlights the energy losses associated with energy production and transmission. It requires energy to convert natural gas or oil to electricity, while energy losses corresponding to renewable energy production are dismissed, as the energy source is of course *free*.

Primary energy savings ([PES](#)) is difference between the amount of energy consumed by the original device (whatever it may be) and the amount of energy consumed by the new device. In relation to this thesis, it will be taken to be the savings of the new heat generation system compared to the old system (conventional gas boiler). Knowledge of the [PEF](#) (or [RES](#)) and [PES](#) can indicate how much CO₂ with a new heating system, and is the foundation of the techno-ecological model of this thesis.

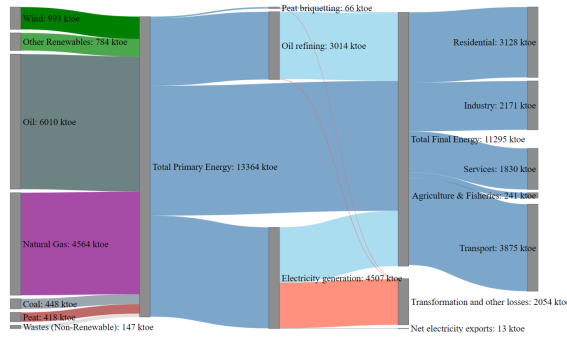


Figure 2.3: Sankey diagram showing PE by fuel type on left and final energy by sector on right [27].

2.4 ELECTRIFICATION OF HEATING

The EU has now for a number of years been pushing for the electrification of heating throughout the union. This has been identified as a clear means to achieve decarbonisation goals, as concerns over global warming become greater. As noted in [Sec. 1.1](#), the residential sector contributes 27% of the final energy consumption, while residential domestic water production and space heating contributes to 80% of that. In Ireland, residential heating accounted for 53% of CO₂ emissions from heating. However, across all sectors, heating and cooling are responsible for half of all final energy consumption in the EU [8]. Therefore, it is clearly evident that decarbonisation of the heating/cooling sector is vital to a) reaching EU targets of lowering CO₂ emissions and b) improving air quality and the reduction of harmful emissions [12]. Although, switching to electrically driven heating systems does not automatically or inherently reduce the carbon emissions, merely, it changes the source of the energy; the electricity must also be decarbonised for this to be the case.

SEAI [27] carried out a comprehensive study on the Irish electrical grid performance as it relates to renewable energy sources and to heating/cooling. According to the report: the share renewable energy to that of the the total energy used in 2020 was

Emission intensity is a measure of how much CO₂ is released per unit of energy produced

13.5% (having missed the EU target of 16%); the share of renewable energy used specifically in heating/cooling was just 6.3%, its target having been 12%; energy from renewable sources grew by 8.9% over the previous year, and the total installed wind energy capacity grew by 4.1%, from 4130 MW to 4310 MW (in the Republic). Overall, the residential energy CO₂ emission has trending downwards over the past decade and a half, falling by 25% since 2005, and the CO₂ intensity of electricity generation is half of its value in 2005, standing at 300 gCO₂/kWh. . These are good signs for the electrification of heating, because in order for the electrification of heating to result in a decarbonising of heating, the electricity production must at least have a lower emission intensity compared to if no electrification process were to take place, but ideally have the prospects of becoming a very low/zero CO₂ intensity matter.

2.5 CONTROLLER AND CONTROL THEORY

Control theory is concerned with the control of dynamic systems with with a desired goal in mind, which is called the reference. A controller manipulates the inputs to a system, usually denoted u in such a way as to alter the output variables or states, y , of the system to follow a given reference. Disturbances d to a system are expected, yet unforeseen inputs to a system which may significantly alter the outputs state. There are two main types of controller, feed-forward, and feedback controllers.

However, they would they no longer qualify as disturbances, and would simply be considered as inputs, but that is by the by.

A feed-forward controller, also known as an open loop controller, controls the system without knowing the current state of the system. This is possible if disturbances are either eliminated, or wholly understood and accounted for. Complete knowledge of the dynamics of the system being controlled would be required and captured by a mathematical model, either by physics and first principles, or by system identification (a model is fitted to

data). The dynamics of the system are inverted by the controller and fed to the system as inputs. Any error in the inversion process results in undesired system states.

Feedback controllers, also known as closed loop controllers are a *much* more common form of controller. The current system state is known to the controller, and the reference and current state information is used to determine the appropriate control inputs. In doing so, a feedback controller inherently changes the dynamics of a system. Feedback controllers usually make systems more stable, however, there is the possibility of making systems less stable and even unstable through controllers. There are many types of feedback controllers, the most common and well understood kind being a linear feedback controller called a Proportional-integral-derivative (PID) controller, or just a PID. Linear controllers assume the general behaviours of the system to be linear. Although, even if the dynamics of system are not, in fact, linear, a PID will still likely be able to control the system appropriately and reach the reference state.

2.5.1 Noise and Error

Measuring the state of the system when preparing to send back information to the PID with a sensor invariably introduces *noise*. Noise is a

Part II

MODEL AND RESULTS

METHODOLOGY

HHS

MODEL

The purpose of models is not to fit the data, but to sharpen the question

— Samuel Karlin

HHS

SENSITIVITY ANALYSIS

[19]

TECHNO-ECONOMIC ASSESSMENT

[19]

CONCLUSIONS

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Part III

APPENDIX

APPENDIX TEST

Lorem ipsum at nusquam appellantur his, ut eos erant homero concludaturque. Albucius appellantur deterruisset id eam, vivendum partiendo dissentiet ei ius. Vis melius facilisis ea, sea id convenire referrentur, takimata adolescens ex duo. Ei harum argumentum per. Eam vidit exerci appetere ad, ut vel zzril intellegam interpretaris.

More dummy text.

A.1 APPENDIX SECTION TEST

Test: [Tbl. A.1](#) (This reference should have a lowercase, small caps A if the option `floatperchapter` is activated, just as in the table itself → however, this does not work at the moment.)

Table A.1: Autem usu id.

LABITUR BONORUM PRI NO	QUE VISTA	HUMAN
fastidii ea ius	germano	demonstratea
suscipit instructor	titulo	personas
quaestio philosophia	facto	demonstrated

$$V = \frac{4}{3}\pi r^3 \quad (\text{A.1})$$

$$= \eta_{\text{s, turbine}} \quad (\text{A.2})$$

$$\text{ch}(f_! \mathcal{F}^\bullet) \text{td}(Y) = f_*(\text{ch}(\mathcal{F}^\bullet) \text{td}(X)) \quad (\text{A.3})$$

Eq. A.1 Eqs. A.1 to A.3 Eqs. A.1 and A.3

A.2 ANOTHER APPENDIX SECTION TEST

Equidem detraxit cu nam, vix eu delenit periculis. Eos ut vero constituto, no vidit propriae complectitur sea. Diceret nonummy in has, no qui eligendi recteque consetetur. Mel eu dictas suscipiantur, et sed placerat oporteat. At ipsum electram mei, ad aequae atomorum mea. There is also a useless Pascal listing below:

*More dummy
textss.*

List. A.1.

Listing A.1: A floating example (listings manual)

```

1 for i:=maxint downto 0 do
2 begin
3   { do nothing }
4 end;
```

COLOPHON

This document was typeset using the typographical look-and-feel `classicthesis` developed by André Miede and Ivo Pletikosić. The style was inspired by Robert Bringhurst’s seminal book on typography “*The Elements of Typographic Style*”. `classicthesis` is available for both \LaTeX and \LyX :

<https://bitbucket.org/amiede/classicthesis/>

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Thank you very much for your feedback and contribution.