

DANIEL JAKOB

OPTIMISING THE BIVALENT TEMPERATURE  
OF A HYBRID HEATING SYSTEM IN THE IRISH  
CLIMATE



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# OPTIMISING THE BIVALENT TEMPERATURE OF A HYBRID HEATING SYSTEM IN THE IRISH CLIMATE

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A NUMERICAL SIMULATION STUDY OF AN AIR-WATER HEAT PUMP  
AND CONVENTIONAL GAS BOILER IN A RESIDENTIAL SETTING

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# CONTENTS

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## I Preamble

1	Introduction	3
1.1	Context	3
1.2	Aim	8
1.3	Motivation	8
1.4	The Problem	9
1.5	Thesis Layout	9
2	Literature Review	11
2.1	Heat Pumps	11
2.1.1	Vapour-Compression Cycle	14
2.1.2	Hybrid Heating Systems	16
2.1.3	Operating Modes of HHS	18
2.1.4	Buffer Tank	19
2.1.5	Frosting and Defrosting	21
2.2	Heating Degree Days and Design Temperatures	23
2.3	Primary Energy	27
2.4	Electrification of Heating	29
2.5	Controllers and Control Theory	31
2.5.1	PID Controllers	32
2.5.2	Noise and Error	33
2.6	Verification & Validation of Model	34
2.6.1	Verification	36
2.6.2	Validation	37

## II Model and Results

3	Methodology	43
4	System Model	45
5	Sensitivity Analysis	47

6	Eco-Economic Assessment	49
7	Conclusions	51
iii	Appendix	
A	Appendix Test	55
A.1	Appendix Section Test	55
A.2	Another Appendix Section Test	56

LIST OF FIGURES

---

Figure 2.1	HHS with an AWHP and condensing gas boiler [dongellini_influence_2021]	17
Figure 2.2	Bivalent-parallel operating scheme [klein_numerical_2014].	18
Figure 2.3	Bivalent operation modes	19
Figure 2.4	Heating Duration Curve	27
Figure 2.5	PE breakdown by fuel type and sector	28

LIST OF TABLES

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Table A.1	Autem usu id	55
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LISTINGS

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Listing A.1	A floating example (listings manual)	56
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## ACRONYMS

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<b>COP</b>	Coefficient of performance
<b>HHS</b>	Hybrid heating system
<b>ASHP</b>	Air source heat pump
<b>PE</b>	Primary energy
<b>PEF</b>	Primary energy factor
<b>HVAC</b>	Heating, Ventilation & Air Conditioning
<b>PES</b>	Primary energy savings
<b>SPF</b>	Seasonal performance factor
<b>SCOP</b>	Seasonal coefficient of performance
<b>RHI</b>	Renewable Heat Incentive
<b>DHWP</b>	Domestic Hot Water Production
<b>AWHP</b>	Air-Water Heat Pump
<b>HP</b>	Heat Pump
<b>HHPS</b>	Hybrid Heat Pump System
<b>RES</b>	Renewable Energy Share
<b>HDD</b>	Heating degree days
<b>PID</b>	Proportional-integral-derivative
<b>RMSE</b>	Root mean square error
<b>CV(RMSE)</b>	Coefficient of Variation of Root Mean Square Error
<b>NMBE</b>	Normalized mean bias error
<b>SMAPE</b>	Symmetrical mean absolute percentage error



## ABSTRACT

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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

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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*

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Daniel Jakob



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Finally, a thanks to my parents for giving me the opportunity to attend university, providing for me and always wanting the best for me. Thank you, I love you.

Dedicated to...





## NOMENCLATURE

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### 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	$6.626\,070\,15\times 10^{-34}\,\text{J Hz}^{-1}$

### Subscripts

$i$	index variable
-----	----------------

### Other Symbols

$\bar{Y}$	average value
$\hat{Y}$	actual or reference value
$N$	total number of data points
$p$	number of adjustable model parameters, for calibration purposes, <b>owen_ashrae_2009</b> suggests $p = 1$
$Y$	simulated or forecast value



## Part I

### PREAMBLE



## INTRODUCTION

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### 1.1 CONTEXT

Largely, throughout the developed world, it is clear that residential energy usage accounts for a large share of total energy use, and of that, space heating and Domestic Hot Water Production (**DHWP**) account for the majority of final energy use. In the USA, Heating, Ventilation & Air Conditioning (**HVAC**) energy use is 50% of all building energy use and in China, **HVAC** energy use is between 50%–70% of building energy use [**ieaorg\_2018**]. It is estimated that by 2050, two thirds of all residential buildings will have a form of air conditioning unit, further increasing these percentage shares. Alone in 2021, space cooling demand rose by 6.5% [**ieaorg\_2022**]. In Europe in 2022, the residential sector was responsible for 27% of final energy consumption [**eurostat\_final\_2018**]. Domestic water heating and space heating collectively account for close to 80% of a household's energy usage in Europe. [**eurostat\_energy\_2020**]. All of this is to say, energy use due to **HVAC** and **DHWP** are high and are expected to continue rising.

Climate change has directly affected heating and cooling design. **owen\_ashrae\_2009** 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 99.6% annual dry-bulb temperature increased 1.52 °C

*Of course, it must be noted that air conditioning naturally rose sharply in no small part due to the COVID-19 pandemic and subsequent isolation rules in place in many parts of the world.*

- The 0.4% annual dry-bulb increased 0.79 °C
- Annual dew point increased by 0.55 °C
- Heating-degree days (base 18.3 °C) decreased by 237 °C d
- Cooling degree-days (base 10 °C) increased by 136 °C d

As of writing,  
continental  
Europe is  
experiencing “the  
most extreme  
event ever seen in  
European  
climatology” with  
a mid-winter  
heatwave  
[pakalolo\_2023]

All of these changes the mentioned parameters point towards an increase in global temperatures. The effects of climate change are affecting how building cooling and heating design is carried out, due to the fact that cooling loads are, in general, becoming lower, while heating loads are generally increasing. Milder winters are allowing Heat Pumps (HPs) to be, ever so slightly more efficient throughout a heating season.

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, due to events on-going as of the writing of this thesis, has indeed become more of an issue than previously thought...Electric heating devices such as HPs convert electricity into heat, creating the sought after link between building heating and the electrical grid [heinen\_electricity\_2016]. 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. [vuillecard\_small\_2011, thomasen\_decarbonisation\_2021] 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 [cso\_2020]. 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 [klein\_numerical\_2014, dongellini\_influence\_2021]. 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 seai\_2020 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, which, as discussed in Sec. 2.3, is generated mostly by non-renewable means in Ireland currently.

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 [cengel\_thermo\_2020], 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 seai\_2020, 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 decommissioned.

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 [ehpa\_2015, nowak\_2018].

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 [omer\_2008, Ochsner\_2007]. 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 [ehpa\_2015].

Frosting is detrimental to the performance of HPs [di\_perna\_experimental\_2015]. 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. An alternative-parallel bivalent system is where the predefined external temperatures for turning on/off the HP/boiler are not coincident, as discussed in Subsubsec. 2.1.3.1. 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 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 tested in-situ in countries such as China [li\_parallel\_2018],

Japan and Korea [[jang\\_continuous\\_2013](#), [park\\_performance\\_2014](#)], North America [[rauschkolb\\_cost-optimal\\_2020](#)], Germany [[klein\\_numerical\\_2014](#)] and other continental European countries [[bagarella\\_annual\\_2016](#), [roccatello\\_analysis\\_2022](#), [amirkhizi\\_cost\\_2020](#), [dongellini\\_influence\\_2021](#), [di\\_perna\\_experimental\\_2015](#)], 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 [[heinen\\_electricity\\_2016](#)]. 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

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### 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 time frame of the year. The space-heating radiators found in existing homes are not suitable for cooling [klein\_numerical\_2014], the cold water in the radiators does not warm the room effectively and condensation on the radiator surface may become an issue.

Because the efficiency of HPs is so dependent on the constantly varying 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 and is considered a more comprehensive metric to establish HP efficiency [seai\_heat\_2020, nowak\_2018]. 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 [seai\_heat\_2020]. 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 HP's SPF must be above 2.5 [eu-114-2014].

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, but usually fall in around the 5 kW to 20 kW range. 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 [bee\_air-source\_2019]. 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 [STIEBEL\_2012]. 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 temperat-

ure which covers 99.0% of the annual heating is  $-0.7^{\circ}\text{C}$ . [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 [[seai\\_heat\\_2020](#)]. 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.

[HPs](#) for residential use are generally classified into two distinct product types: low-temperature and high-temperature, which refers to the flow temperature of the [HP](#). Low-temperature [HPs](#) typically heat water to a maximum temperature of  $55^{\circ}\text{C}$

The flow temperature of a [HP](#) in a heating system plays a crucial role in the performance and efficiency of the system. It refers to the temperature of the fluid, typically water or refrigerant, as it flows through the [HP](#)'s evaporator and condenser coils. A lower flow temperature in the evaporator coil allows the heat pump to absorb more heat from the source, increasing the energy provided to the in-pump loop which is passed to the condenser coils and subsequently the heat distribution/buffer tank loop [[nowak\\_2018](#)]. The flow temperature is affected by the initial

temperature of the refrigerant and also how much electrical energy is being provided to the compressor

The flow temperature also affects the overall temperature of the heating system, as it determines the temperature of the water or refrigerant that is circulated through the building's heating system. A higher flow temperature allows the heat pump to provide more heat to the building, making it warmer. However, a higher flow temperature also results in a lower COP (coefficient of performance) of the heat pump, meaning it is less energy efficient.

#### 2.1.1 *Vapour-Compression Cycle*

The vapour-compression cycle is a process used in [HPs](#) and refrigeration systems to transfer heat from a low temperature heat source to a high temperature heat sink [[cengel\\_thermo\\_2020](#)]. The cycle begins when a refrigerant, typically in a liquid state, is vaporised in an evaporator. As the refrigerant vaporises, it absorbs heat from the surrounding low temperature heat source, such as the air inside a refrigerator or the ground in a geothermal [HP](#).

Next, the vaporised refrigerant is pressurised and moves through a compressor. As the refrigerant is compressed, its temperature and pressure increase. The hot, high pressure refrigerant vapour is then passed through a condenser, where it releases heat to the surrounding high temperature heat sink, such as the air outside a refrigerator or the air inside a home in a [HP](#).

As the refrigerant gives up heat, it condenses back into a liquid. The liquid refrigerant is then passed through an expansion valve, where its pressure is reduced and it begins to evaporate once again. This reduction in pressure causes the refrigerant to absorb



additional heat, which helps to further cool the low temperature heat source.

The refrigerant continues through the cycle, alternating between the evaporator, compressor, and condenser, until the desired level of heat transfer is achieved. In a [HP](#), the cycle is reversed during the heating mode, transferring heat from the outside air to the inside of a home.

While the vapour-compression cycle is not identical to the Rankine cycle or the Carnot cycle, it shares some similarities and can be thought of as a practical implementation of these theoretical models.

The Rankine cycle is a thermodynamic cycle that describes the operation of a heat engine, such as a steam power plant [[cengel\\_thermo\\_2020](#)]. The cycle consists of four processes: pressurisation, heating, expansion, and cooling. These processes are similar to those in the vapour-compression cycle, in which a working fluid (such as water or steam) is pressurised and heated, causing it to expand and generate work before being cooled and condensed back into a liquid.

Like the Rankine cycle, the Carnot cycle is a theoretical model of a heat engine that describes the maximum possible efficiency of a heat engine operating between two temperature reservoirs. The Carnot cycle consists of four reversible processes: isothermal expansion, adiabatic expansion, isothermal compression, and adiabatic compression. The efficiency of the Carnot cycle is determined by the temperature difference between the heat source and the heat sink, and it serves as a benchmark for the performance of real heat engines [[cengel\\_thermo\\_2020](#)].

### 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 [blackman\_study\_2019]. 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 [park\_performance\_2014, bagarella\_annual\_2016, dongellini\_influence\_2021, rauschkolb\_cost-optimal\_2020]. 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 to *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 an optimal indoor temperature.

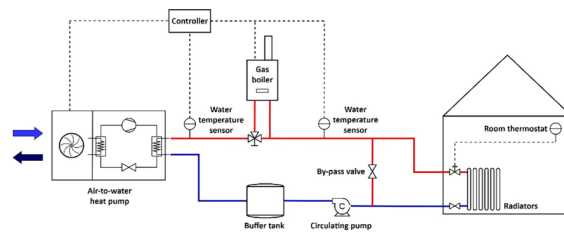


Figure 2.1: [HHS](#) with an [AWHP](#) and condensing gas boiler [dongellini\_influence\_2021]

[heinen\\_electricity\\_2016](#) [[heinen\\_electricity\\_2016](#)] concluded that [HHSs](#) that use a combination of electricity and gas as the energy source for the heating system can provide the greatest economic benefits when compared to other types of hybrid heating technologies in a combined power-residential heat system. The investment costs of these systems may vary depending on factors such as the size of the system, the specific technology used, and the cost of electricity and gas in the area. However, overall, a [HHPS](#) that utilises a combination of electricity and gas as the energy source is likely to have the most favourable cost-benefit ratio.

In monovalent systems the entire heat demand, regardless of ambient temperature is supplied with the HP, but there is hardly any reason to operate in this mode and requires an oversized HP.

2.1.3 Operating Modes of HHS

2.1.3.1 Bivalent-Parallel Operation

In this study, the bivalent-parallel operation paradigm for a HHS is used, which is where a controller determines whether to solely run the HP or conventional gas boiler, or so run them in parallel. **buday\_2014** [**buday\_2014**] explains: at temperatures below a certain threshold ( $T_{\text{cutoff}}$ ), only the boiler is used, see: domain 1 in Fig. 2.2. Between ( $T_{\text{cutoff}}$ ) and a second threshold ( $T_{\text{biv}}$ ), both the boiler and HP are used (domain 2). At temperatures above ( $T_{\text{biv}}$ ), only the HP is used (domain 3). The second threshold ( $T_{\text{biv}}$ ) is the temperature at which the HP can meet the building's heat demand, and ( $T_{\text{cutoff}}$ ) is set to a value such that, when ambient temperatures are above this value, the HP is ecologically and economically efficient. The optimisation of the bivalent temperature,  $T_{\text{biv}}$ , is the crux of this thesis. The cut-off temperature can be calculated using the boiler and HP efficiency and the Primary energy factors (PEFs) of the heat sources.

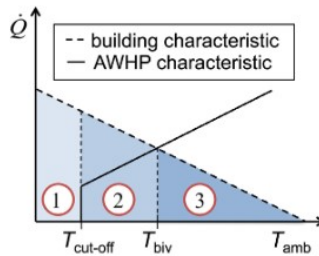


Figure 2.2: Bivalent-parallel operating scheme [klein\_numerical\_2014].

2.1.3.2 Bivalent-Alternative Operation

In bivalent-alternative operation, the controller has two options in contrast to the three outlined in Subsubsec. 2.1.3.1, either solely use the HP or solely use the gas boiler [**buday\_2014**]. Be-

low the set bivalent point, the heat demand is entirely provided by the auxiliary heating device, as see in Fig. 2.3. Above the bivalent temperature, the heat demand is entirely provided by the HP. This operation places the  $T_{\text{biv}}$  and  $T_{\text{cutoff}}$  coincident [buday\_2014, klein\_numerical\_2014].

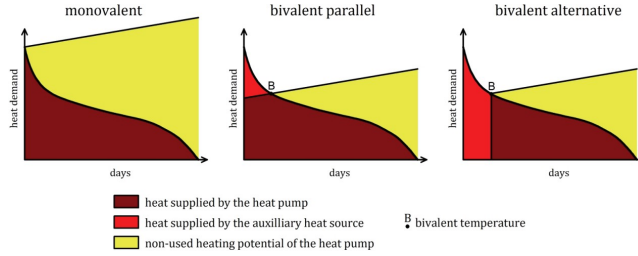


Figure 2.3: Types of bivalent HHS operation modes visualised through heating duration curves [buday\_2014]. Note:  $T_{\text{cutoff}}$  is not clearly shown in this figure.

#### 2.1.4 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 [owen\_ashrae\_2009]. 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](#) [[klein\\_numerical\\_2014](#), [roccatello\\_analysis\\_2022](#)]. The controller is able to make use of the [HPs](#) “most profitable working conditions” thanks to the presence of the buffer [[dettorre\\_economic\\_2018](#)]. It has been found that when a buffer tank is present in the [HP](#) circuit, [SPF](#) increases as the size of the [HP](#) decreases [[mugnini\\_variable-load\\_2021](#)]. [mugnini\\_variable-load\\_2021](#) [[mugnini\\_variable-load\\_2021](#)] confirmed this for all sizes of [HPs](#) simulated, the smallest buffer tank having a capacity of 200 L. [STIEBEL\\_2012](#) [[STIEBEL\\_2012](#)] suggest to size the buffer tank so large as to at least be able to defrost the coils.

[ASHPs](#) can experience negative effects when operated at partial load, such as on-off cycle deterioration. This is caused by losses in the start-up and standby stages, where there is a delay in heating output and power consumption but no heat produced. To prevent these losses and excessive on-off cycles, a buffer tank can be installed in series with the heat pump, providing the hydraulic switch mentioned earlier [[bagarella\\_cycling\\_2013](#)]. In addition to protecting the heat pump from negative effects of partial load operation, the buffer tank also plays a role in maintaining indoor thermal comfort during reverse defrosting, as discussed in [Subsec. 2.1.5](#).

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 [[klein\\_numerical\\_2014](#)]. 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 [[roccatello\\_analysis\\_2022](#)] and [[klein\\_numerical\\_2014](#)], 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\\_numerical\\_2014](#) found that the volume

of the buffer tank had very limited effect on the system performance. [dongellini\\_influence\\_2021](#) [[dongellini\\_influence\\_2021](#)] 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 [[dettorre\\_economic\\_2018](#)]

### 2.1.5 *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 [HPs](#), a few ranges of temperatures at which frosting occurs has been found in the literature [[sandstrom\\_frosting\\_2021](#)] finding a range of  $-15^{\circ}\text{C}$  to  $6^{\circ}\text{C}$  at a r.h. of  $\approx 90\%$ , while [[kropas\\_experimental\\_2021](#)] found frost formation to begin when the ambient air temperature was below  $3.5^{\circ}\text{C}$  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 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. [[zhang\\_experimental\\_2018](#)] 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 SPF of the HP as the house is being actively cooled by the HP in order to heat up the outdoor coils and fins to melt away the frost, which in turn causes the auxiliary heater to work even harder to maintain a comfortable indoor temperature. 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 HPs cycles. Resistive heaters are very expensive to run and negatively affect the COP of the HP.

[amer\_review\_2017] found that the reverse cycling method resulted in a higher average COP than the other two methods, over a series of multiple reverse cycle defrostings. Additionally, [bagarella\_annual\_2016] found that a buffer tank can ensure thermal comfort during reverse cycle defrosting, due to being able to use the stored energy from the buffer tank to melt the frost on the outdoor coils without actively cooling the indoor space due to the inherent decoupling of the heat production and distribution loops created by the buffer tank. [bagarella\_annual\_2016] agreed with [dong\_2012] that the *defrosting efficiency* of the reverse cycling method is around 60%. This is the ratio of energy supplied to the coils to the actual energy transferred to the frost for melting.

## 2.2 HEATING DEGREE DAYS AND DESIGN TEMPERATURES

Heating degree dayss (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 heat-

ing requirement of a specific building is directly proportional to the [HDD](#) [[chartered\\_institution\\_of\\_building\\_services\\_engineers\\_environmental\\_2006](#)].

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 the first of the three equations in [Eq. 2.1](#) is made use of. This total is found by summing the daily temperatures differences and can be seen in [Eq. 2.2](#).

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

[chartered\\_institution\\_of\\_building\\_services\\_engineers\\_environmental\\_2006](#) has chosen a base temperature of 15.5 °C. [owen\\_ashrae\\_2009](#) 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 [[degreedays](#)] 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. [owen\\_ashrae\\_2009](#)

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 **owen\_ashrae\_2009**, the 99.6% design temperature in Dublin Airport is  $-1.9^{\circ}\text{C}$  while the 99.0% design temperature is  $-0.7^{\circ}\text{C}$ . 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  $\sim 35$  hours of the year.

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 [**klein\_numerical\_2014**]. An oversized heating system would be very inefficient due to frequent on-off cycling, which also results in rapid degradation of heating system components. Oversized heating systems also result in potentially uncomfortable indoor temperatures as rooms are unequally heated. Finally, oversized systems have higher maintenance costs and significantly higher initial investment costs.

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 [**rauschkolb\_cost-optimal\_2020**]. A design-day file is a special weather file created with design conditions in mind. Based on the design temperature parameter, **owen\_ashrae\_2009** 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 [**owen\_ashrae\_2009**]. 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).

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

*for the purposes of the simulation(s) concerning this thesis, the 0.4 percentile, and any cooling-nessecary-temperatures for that matter, are*

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 [ $\text{kW h}^{-1}$ ] against number of hours the heating load is equal to or above a selected percentage of design load. For example, as illustrated in Fig. 2.4, 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 required 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.

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.

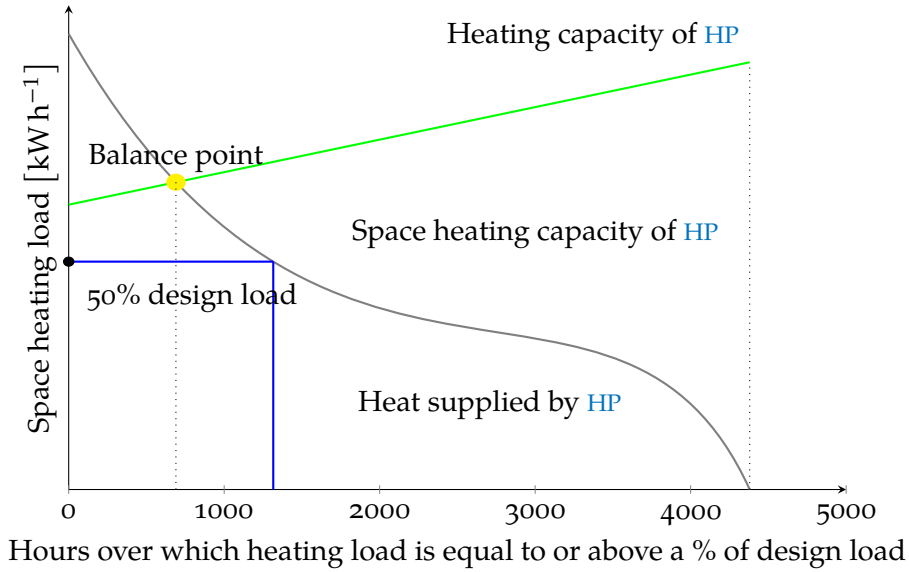


Figure 2.4: Heating Duration Curve

## 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 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 [nowak\_2018]. The PEF is used to evaluate the environmental impact of a system by considering the primary energy consumption, which includes the energy required to produce and distribute the energy source, such as the energy used to extract and transport fossil fuels. For example, a

hydroelectric power plant with a **PEF** of 1, means that the energy used to generate electricity is equal to the energy consumed. On the other hand, a coal-fired power plant with a **PEF** of 2.5, means that 2.5 units of **PE** are consumed to generate 1 unit of electricity. Therefore, hydroelectric power plants are considered more environmentally friendly than coal-fired power plants. [bianco\_estimation\_2017] found that with a suitably high diffusion of **RES** in an electrical grid, significant Primary energy savings (**PES**) can be obtained through the use of **HPs** for space heating and can overall promote energy savings in buildings, in turn reducing CO<sub>2</sub> emissions [nowak\_2018].

Fig. 2.5 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*.

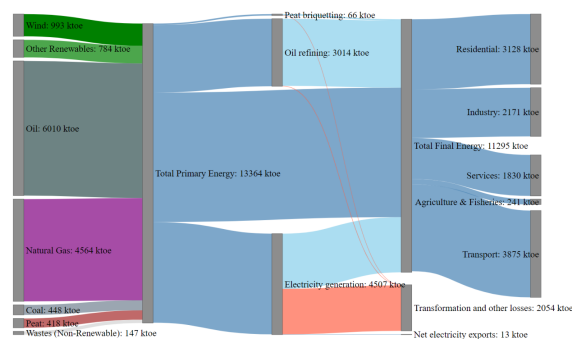


Figure 2.5: Sankey diagram showing **PE** by fuel type on left and final energy by sector on right [seai\_energy\_2021].

**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 as sole heat

production). Knowledge of the PEF, PES and the make-up of the fuel types and shares in the PE, i.e., the RES, can indicate how much CO<sub>2</sub> is consumed at any instance with a heating system [bianco\_estimation\_2017], and is the foundation of the technological model of this thesis.

The RES of an electrical grid refers to the proportion of electricity generated from renewable energy sources, such as solar, wind, hydro, geothermal, and biomass, compared to the total electricity generation. It is a measure of how much of the electricity being consumed by a country or region is coming from renewable sources. For example, if an electrical grid generates 50 GW of electricity and 20 GW of it is generated from renewable sources, the RES of that grid is said to be 40%.

The RES is an important metric to measure the progress towards decarbonization and the reduction of greenhouse gas emissions in the energy sector. Governments and international organisations have set targets for the increasing share of renewable energy in the electricity mix as a means of reducing the dependence on fossil fuels and reducing the emissions of greenhouse gases. Knowing the RES of an electrical grid can also help understand the potential for further integration of renewable energy sources and the necessary investments in infrastructure and technology to achieve the goals set by the government or international organizations. In addition, the RES of an electrical grid can also impact the stability of the grid and the integration costs, it is important for grid operators and policy makers to consider this metric when planning for future energy systems.

## 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 CO<sub>2</sub> emissions from heating. However, across all sectors, heating and cooling are responsible for half of all final energy consumption in the EU [[an2016strategy](#)]. Therefore, it is clearly evident that decarbonisation of the heating/cooling sector is vital to a) reaching EU targets of lowering CO<sub>2</sub> emissions and b) improving air quality and the reduction of harmful emissions [[epri2018us](#)]. 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\\_energy\\_2021](#) [[seai\\_energy\\_2021](#)] 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 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 CO<sub>2</sub> emission has trending downwards over the past decade and a half, falling by 25% since 2005, and the CO<sub>2</sub> intensity of electricity generation is half of its value in 2005, standing at 300 gCO<sub>2</sub>/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

*Emission  
intensity is a  
measure of how  
much CO<sub>2</sub> is  
released per unit  
of energy  
produced*



electrification process were to take place, but ideally have the prospects of becoming a very low/zero CO<sub>2</sub> intensity matter.

## 2.5 CONTROLLERS 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 [Franklin2014].

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.

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

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 Franklin2014. 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 [[Rames\\_2012](#)].

In a [HHS](#), controllers are used to manage the operation of the different heating technologies and ensure that they are used in the most efficient and effective way possible [[di\\_perna\\_experimental\\_2015](#), [bagarella\\_annual\\_2016](#), [roccatello\\_analysis\\_2022](#), [demirezen\\_feasibility\\_2021](#), [mugnini\\_variable-load\\_2021](#), [bianco\\_estimation\\_2017](#)]. The controllers in a [HHS](#) are typically responsible for a number of tasks, including monitoring the temperature inside and outside the building, determining the best heating technology to use based on the current conditions, and controlling the operation of the heating technologies to maintain a comfortable and consistent temperature.

For example, when the outside temperature is cold, the controller may determine that it is most efficient to use the gas furnace to heat the building. When the outside temperature is mild, the controller may determine that it is more efficient to use the [HP](#), which uses less energy than the gas furnace. Very advanced controllers may also use predictive algorithms and weather forecasts to anticipate changes in temperature and adjust the heating system accordingly by storing a lot of heat in the buffer tank during a warm period right before a cold period [[demirezen\\_feasibility\\_2021](#)].

### 2.5.1 *PID Controllers*

[PID](#) controllers are a type of feedback control system that are commonly used in a wide variety of systems to maintain a desired

output or setpoint. The acronym refers to the three components of the control algorithm used by the controller. [PID](#) controllers work by continuously calculating an error value that represents the difference between the desired setpoint and the current output of the system. **Rames\_2012** [**Rames\_2012**] explains that this error value is then used to calculate and apply a correction to the system, based on the three components of the [PID](#) algorithm:

- The proportional component applies a correction proportional to the error value. This allows the controller to quickly respond to large errors and make large corrections.
- The integral component applies a correction based on the accumulated error over time. This helps to eliminate steady-state errors and ensure that the system eventually reaches the desired setpoint.
- The derivative component applies a correction based on the rate of change of the error. This helps to dampen the system's response and prevent overshoot and oscillation.

[PID](#) controllers are used in a wide variety of systems, including mechanical systems like motors and actuators, temperature control systems, and chemical process control systems. They are often preferred over other control algorithms because they are relatively simple to implement and can provide stable and accurate control of the system's output.

### 2.5.2 *Noise and Error*

Noise and error are common sources of problems in control systems. Noise refers to random variations in the system's output that are not caused by the control signal, while error refers to the difference between the desired setpoint and the actual output of the system. Noise and error can have a number of adverse effects on the performance of a control system, including reduced

accuracy and stability, as well as increased oscillation and overshoot. To deal with noise and error in control systems, a number of different approaches can be used. One approach is to use a filter to remove noise from the system's output signal. This can be done using a low-pass filter, which removes high-frequency noise, or a high-pass filter, which removes low-frequency noise. Another approach is to use a model-based control algorithm, which uses a mathematical model of the system to predict the system's output and apply appropriate control signals. This can help to reduce the effects of noise and error by using the model to compensate for them. Furthermore, another approach is to use a robust control algorithm, which is designed to be resistant to the effects of noise and error. Robust control algorithms typically use a combination of feedback and feed-forward control, as well as advanced control techniques like gain scheduling and optimization, to achieve robust performance in the presence of noise and error.

## 2.6 VERIFICATION & VALIDATION OF MODEL

Verification and validation are two important processes that are used to assess the credibility and reliability of a simulation model. While these terms are often used interchangeably in common parlance, they have distinct meanings and serve different purposes.

Verification is the process of ensuring that a simulation model is implemented correctly and accurately represents the underlying mathematical equations, assumptions, and physical phenomena. Verification ensures that the simulation code is free from coding errors and that the numerical algorithms are implemented correctly, and confirms whether the model behaves as the modeller expects. This process involves checking the model against ana-

lytical solutions or known results and comparing the simulation output with the expected results.

Validation, on the other hand, is the process of determining whether a simulation model accurately represents the real-world system it is intended to simulate. Validation involves comparing the model output to real-world observations and data to assess the model's accuracy in predicting system behaviour. This process also involves assessing the model's sensitivity to input parameters and assumptions. The model's underlying values (e.g., insulation thickness, floor tile conductivity, etc.) are altered and calibrated to fit the real-world data.

Building energy simulation models must undergo verification and validation due to various sources of uncertainty arising naturally as a result of converting a real-life problem to a mathematical model to a numerical model. Four sources of uncertainty particular to building energy simulation are identified by [coakley\_review\_2014, DEWIT2002951] as:

- Specification uncertainty arises from incomplete or inaccurate specifications of the building or systems being modelled.
- Modelling uncertainty results from simplifications and assumptions of complex physical processes.
- Numerical uncertainty is introduced during the discretisation and simulation of the model.
- Scenario uncertainty comes from external conditions imposed on the building, such as outdoor climate conditions and occupant behaviour.

### 2.6.1 Verification

For the purposes of model verification, a series of small simulation runs were carried out to test whether the model was behaving as expected. It was noted during the early runs of the simulation, the air in `zone3_floor1` was dramatically increasing in temperature during a certain day in early January. It was discovered that this was due to relatively high levels of direct and horizontal solar irradiation entering the room through the large, southerly facing window. The first verification test consists of loosely quantifying the solar irradiation energy gain into the room with the existing window from the model, and comparing this to a simulation run where the window was purposely shrunk to circa one tenth of its original area.

The ubiquitous heat capacity equation was utilised in quantifying the irradiation gain:

$$Q = mc\Delta T \quad (2.3)$$

Where  $Q$  is the heat energy in watts,  $m$  is the mass of air in the room,  $c$  is the specific heat capacity of air ( $C_{v_{\text{air}}} = 0.718 \text{ kJ kg}^{-1} \text{ K}^{-1}$ ) and  $\Delta T$  is the change in temperature of the air in the room (i.e., difference between temperature at a chosen time in hours leading up to the event, and the peak temperature after the bulk of the simulation day's irradiation). The mass of air in this room was found by taking the volume ( $31 \text{ m}^3$ ) and multiplying it by the density of air at a mean temperature ( $\sim 1.204 \text{ kg m}^{-3}$ ). The heat gained by the room with the large window was found to be 420 J while with the small window it was found to be 420 J. This is to be expected as a larger window would justly allow more irradiance to (semi-)directly into the room.

The next test was to check if heat was being conducted through the interior walls of the building. A room was chosen, and its

temperature was purposely raised to an unnatural level of 60 °C. One would expect that the temperature of the adjacent rooms would increase by means of conduction.<sup>1</sup> The test involved comparing the adjacent room temperatures to the corresponding room temperatures in the case where the chosen room's temperature was not artificially raised. The temperature was found to increase an average of 6 °C across the 4 neighbouring rooms.

### 2.6.2 Validation

The validation process of a building energy simulation model is a crucial step in ensuring that the model accurately predicts the energy performance of the building. The [ashrae\\_guideline\\_project\\_committee\\_14\\_ashrae\\_guideline\\_project\\_committee\\_14\\_ashrae\\_2014](#) provides a comprehensive framework for validating building energy simulation models. This guideline outlines a step-by-step process for validating the simulation model and includes criteria for evaluating the accuracy of the model. The validation process involves comparing the model results with actual building energy consumption data and performing statistical analysis to determine the level of accuracy. In the validation process, three statistical tools are employed to evaluate the accuracy of the simulation model in this thesis. The first two are suggested by [owen\\_ashrae\\_2009](#) while the last is used as its properties are distinct from the first two and provides a useful measure of absolute error.

Coefficient of Variation of Root Mean Square Error ([CV\(RMSE\)](#)) is a statistical tool used to determine the degree of error between the simulated and actual data and is a commonly used tool in the validation process of building energy simulation models because it takes into account the variability in the actual data. It calculates

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<sup>1</sup> Door and window openings were not modelled as part of this simulation. The air infiltration rate was increased slightly to compensate for this. However, this also means interzonal airflow was also not modelled.

the Root mean square error (RMSE) as a percentage of the mean of the actual data, which makes it a useful metric for evaluating the model's accuracy across a range of operating conditions. A lower CV(RMSE) value indicates that the model is a better predictor of the actual building energy performance. The CV(RMSE) tool is particularly useful when comparing the performance of different models or when assessing the impact of different input parameters on the model's accuracy. [coakley\_review\_2014] said: "[CV(RMSE)] allows one to determine how well a model fits the data by capturing offsetting errors between measured and simulated data. It does not suffer from the cancellation effect.". The formula for CV(RMSE) is given by Eq. 2.4.

$$CV(RMSE) = \frac{100}{\bar{Y}} \sqrt{\frac{\sum_{i=1}^N (Y_i - \hat{Y}_i)^2}{N - p}} = \frac{RMSE}{\bar{Y}} \quad (2.4)$$

Normalized mean bias error (NMBE) is another statistical tool used in the validation process, measuring the bias of the model. It provides a measure of the difference between the mean of the simulated and actual data as a percentage of the actual data. A zero NMBE value indicates that the model is unbiased, while a positive or negative NMBE value indicates overestimation or underestimation, respectively. The NMBE tool is useful in identifying systematic errors in the model, which can occur due to incorrect model assumptions, data input errors, or other issues. It helps to identify the direction and magnitude of the bias, which is important for developing strategies to improve the model's accuracy. The formula for NMBE is given by Eq. 2.5.

$$NMBE = \frac{100}{\bar{Y}} \frac{\sum_{i=1}^N (Y_i - \hat{Y}_i)}{N - p} \quad (2.5)$$

Symmetrical mean absolute percentage error (SMAPE), first proposed by MAKRIDAKIS1993527 [MAKRIDAKIS1993527] and



approved by many [tofallis\_better\_2015,khendek\_system\_2018,kim\_new\_2016], is a statistical tool that measures the absolute percentage difference between the simulated and actual data. Unlike the previous two tools, SMAPE is symmetric and thus gives equal weight to overestimation and underestimation. A lower SMAPE value indicates higher model accuracy. It is an extension of the MAPE method which has the flaw of being asymmetric in its treatment of over- and underprediction of the actual value, overpredictions being penalised harder than underpredictions. There are three common definitions of SMAPE, each with different properties, however, this thesis chooses to use the definition which outputs values as a percentage error between 0% and 100% as this is most easily interpretable and comparable. The formula for SMAPE is given by Eq. 2.6.

$$\text{SMAPE} = \frac{100}{N} \sum_{i=1}^N \frac{|Y_i - \hat{Y}_i|}{|\hat{Y}_i| + |Y_i|} \quad (2.6)$$

ashrae\_guideline\_project\_committee\_14\_ashrae\_2014 [ashrae\_guideline\_project\_committee\_14\_ashrae\_2014], suggest different tolerances for data calibrated by monthly or by hourly data for the CV(RMSE) and NMBE statistical methods. The experimental data was collected by monthly intervals. owen\_ashrae\_2009 [owen\_ashrae\_2009] suggests tolerances of <15% for CV(RMSE) and  $\pm 5\%$  for NMBE. A simulation is said have high levels of model prediction performance if absolute percentage error values outputted by SMAPE are less than 20% and great levels if less than 10%.



## Part II

### MODEL AND RESULTS



## METHODOLOGY

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## SYSTEM MODEL

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

— Samuel Karlin

HHS





## SENSITIVITY ANALYSIS

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[li\_parallel\_2018]



## ECO-ECONOMIC ASSESSMENT

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## 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;
```

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## 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  $\text{\LaTeX}$  and  $\text{\LyX}$ :

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

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Thank you very much for your feedback and contribution.