Advancing Industrial Participation in Demand Response within National Electricity Grids through Systematic Asset Selection, Risk Assessment and Modelling Approaches

Alexander Brem

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Advancing Industrial Participation in Demand Response within National Electricity Grids through Systematic Asset Selection, Risk Assessment and Modelling Approaches

Alexander Brem
BEng (Hons)

Thesis submitted for the degree of
Doctor of Philosophy

Department of Mechanical, Biomedical and Manufacturing Engineering

Supervisors: Dr. Ken Bruton, Dr. Paul O’Sullivan, Dr. Andrew Cashman

Submitted to Munster Technological University, 31st August 2022
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<td>Air Handling Unit</td>
</tr>
<tr>
<td>ASHRAE</td>
<td>American Society of Heating, Refrigerating and Air-Conditioning</td>
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<tr>
<td>BB</td>
<td>Black Box</td>
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<tr>
<td>BER</td>
<td>Building Energy Rating</td>
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<tr>
<td>BESS</td>
<td>Battery Energy Storage System</td>
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<td>BMS</td>
<td>Building Management System</td>
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<td>Budapest</td>
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<td>Bow Tie</td>
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<td>CAV</td>
<td>Constant Air Volume</td>
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<td>Community Choice Aggregation</td>
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<td>CHP</td>
<td>Combined Heat and Power</td>
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<tr>
<td>CLHG</td>
<td>Cork Lower Harbour Group</td>
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<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>CSO</td>
<td>Central Statistics Office</td>
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<tr>
<td>CVPP</td>
<td>Commercial Virtual Power Plant</td>
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<td>DER</td>
<td>Distributed Energy Resource</td>
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<tr>
<td>DOE</td>
<td>Design of Experiments</td>
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<tr>
<td>DR</td>
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<td>DS3</td>
<td>“Delivering a Secure, Sustainable Electricity System”</td>
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<td>HEMS</td>
<td>Home Energy Management System</td>
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<td>HOMER</td>
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<td>Intergovernmental Panel on Climate Change</td>
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<td>Description</td>
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<tr>
<td>I-SEM</td>
<td>Integrated Single Electricity Market</td>
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<td>ISO</td>
<td>International Organisation for Standardisation</td>
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<td>LIEN</td>
<td>Large Industry Energy Network</td>
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<td>MAE</td>
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<td>Mean Bias Error</td>
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<td>NDC</td>
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<td>nZEB</td>
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<td>PC</td>
<td>Pearson’s Correlation</td>
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<td>Primary Operating Reserve</td>
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<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>R</td>
<td>Resistance</td>
</tr>
<tr>
<td>R²</td>
<td>R-squared, Coefficient of determination</td>
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<tr>
<td>RC</td>
<td>Resistance Capacitance</td>
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<td>RES</td>
<td>Renewable Energy Source</td>
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<td>Root Mean Squared Error</td>
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<td>Tertiary Operating Reserve</td>
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<td>TRNSYS</td>
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<td>Transmission System Operator</td>
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<td>Technical Virtual Power Plant</td>
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<td>Waste-to-Energy</td>
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## Nomenclature

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<tr>
<td>C</td>
<td>Specific Heat Capacity</td>
<td>[J/kgK]</td>
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<td>C_A</td>
<td>Specific Heat Capacity of Air</td>
<td>[J/kgK]</td>
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<td>f_k</td>
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<td>[°C]</td>
</tr>
<tr>
<td>UA</td>
<td>UA Values</td>
<td>[W/m^2K]</td>
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<tr>
<td>\dot{V}</td>
<td>Volumetric Flow of Supply Air</td>
<td>[m^3/s]</td>
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<tr>
<td>V_Z</td>
<td>Zone Volume</td>
<td>[m^3]</td>
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<tr>
<td>\alpha</td>
<td>Solar Absorptivity</td>
<td>[W/mK]</td>
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<tr>
<td>\rho</td>
<td>Density</td>
<td>[kg/m^3]</td>
</tr>
<tr>
<td>\rho_A</td>
<td>Density of Air</td>
<td>[kg/m^3]</td>
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List of Definitions

Blackout

A total crash of the electricity grid network due to an imbalance between power generation and consumption.

Demand Response

A process that changes electrical consumption from its regular consumption pattern without jeopardising its primary function, in response to grid requirements and financial incentives at times of high electricity market variability to prevent threats to grid reliability.

Demand Side Management

Planning, implementation and monitoring of utility activities designed to influence the use of electricity in ways that will produce desired changes in the utility’s load shape, pattern and magnitude.

Flexible Capacity

A defined capacity that can shift the time that energy is drawn from or exported to the grid by behind-the-meter resources in response to an external signal.

Prosumer

An entity that is both a producer and consumer of energy and is represented to the grid as a two-way flow of energy or both an electrical load and generation resource.

Scalar

A payment multiplier added to existing participation payments, to incentivise specific practices further for the benefit of the transmission system operator.

Virtual Power Plant

A mechanism for controlling and managing an interconnected aggregation of assets, including but not limited to, distributed energy resources, energy storage systems and flexible loads, enabling them to participate in the market in the same manner as a conventional power plant.
I, Alexander Brem, certify that this thesis is my own work and has not been submitted for another award at any other institution. I have read and understood Munster Technological University’s Code of Good Practice in Research and confirm that all external references and sources are clearly acknowledged and identified within the contents of this thesis.

Alexander Brem

02/09/22

Date

Ken Bruton

02/09/22

Date
Abstract

Increasing the flexible capacity on national electricity grids will be key to maintain reliable control as the levels of renewables continue to increase annually. The industrial sector has been identified as being capable of contributing and potentially offering flexible capacities, following appropriate investigation. The aim of this thesis is to develop the knowledge, advance the engagement and encourage additional participation in national demand response programmes from the industrial sector to provide this flexibility. The potential within this sector, facilitated by the smart grid and demand response concepts is outlined, specifically detailing their benefits, driving factors and potential barriers as part of a detailed literature review. Based on these findings, a novel and appropriate six-step framework is presented, which assists the systematic identification, categorisation and risk-assessment of industrial assets, allowing suitably low-risk assets to be highlighted for demand response participation, providing flexible capacity to the national grid.

Implementing the framework on a case study industrial site helps to ensure its suitability and provide a demonstration for prospective participants. Following the framework steps, the most suitable selected assets are subjected to further evaluation using the developed risk-assessment modelling tool encompassed in the framework. Presenting a modelling tool to assess the operational risk of selected air handling units participating in national demand response programmes. This modelling analysis illustrates the low-risk capabilities of the selected industrial air handling unit, also highlighting specific areas for further risk mitigation. This demonstrates that there is very low risk of these assets participating in the shorter demand response events, especially five-minute shutoffs, even in the most extreme scenarios. Also outlining that the case study air handling unit could have responded to previous actual grid frequency events, incurring no risk for at least twenty-minutes.

Following the implementation, 35 kW to 75 kW of flexible capacity was found to be available on the case study industrial site. The impact of the identified low-risk assets participating in demand response is also outlined on a local, regional and national scale, demonstrating the impact achievable using this framework. Based on the scaling scenarios, flexible capacities between 7 MW and 18.5 MW and even up to 54 MW in the largest scenario considered may be achievable in Ireland. These capacities, comparable to some existing power plants, would help to maintain reliable control of the electricity grid. The site benefits including financial and environmental performance are also investigated, demonstrating the value and impact to encourage further engagement from this sector. The basic, lowest risk scenarios present potential earnings of €3,000 to €7,000 annually for participants, increasing from €11,000 to €26,500 once appropriate scalars are applied, which may account for 14% of a representative industrial site’s electricity expenditure. Participating sites may even earn between €21,500 and €167,000 annually if all stipulations are satisfied. Furthermore, the analysis demonstrates that a participating site could have reduced its annual CO₂ emissions by up to 1.4 tonnes by engaging in this concept. Overall, the research presented in this thesis demonstrates the low-risk flexible capacity available from the industrial sector, which would benefit the participant and have a positive impact on the national electricity grid.
Acknowledgements

There are numerous people that have supported me throughout the years and made getting to the end of this PhD possible. First and foremost, I absolutely could not have done it without Ken Bruton. His encouragement, ability to always have time for even minor questions and wealth of knowledge and advice on all things academic, professional and everything in between ensured I couldn’t have asked for a better supervisor.

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Chapter 1

Introduction

The following chapter introduces this thesis, providing an outline of the research motivations, background and overall context. The Irish perspective and its specific details are presented, highlighting the unique electricity system and its associated challenges and opportunities, including maintaining grid reliability. Key concepts in this area, like the value of smart and flexible electricity grids are also introduced. The industrial sectors’ potential to provide flexible capacity and benefit the wider electricity grid is illustrated as a valuable area for further investigation. In the remaining sections, the objectives and overall thesis structure are defined, in addition to a summary of the key contributions and novelty presented in this thesis and its value to the wider research area.

1.1 Research Motivation

1.1.1 Background and Context

According to the Intergovernmental Panel on Climate Change (IPCC), “It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred” [1]. It is therefore imperative that action is taken to mitigate the continued impact on the climate and implement further measures to reduce and correct the global influence of human activities. An initial step taken internationally and enforced by the Paris Agreement was the submission of Nationally Determined Contributions (NDCs) including post-2020 climate action plans. The aim of the Paris Agreement was to hold global warming to well below 2°C relative to pre-industrial levels, while pursuing efforts to limit warming to 1.5°C [2]. However, even if the previously submitted NDCs were fully implemented, their combined mitigation impact would fall far short of what is required to limit global warming to well below 2°C, let alone 1.5°C [3]. This is reinforced by the current warming projections for 2100 falling between 2.7°C and 3.1°C based on current policies and even the optimistic net zero emission target scenario likely only falling just below 2.2°C [4]. This highlights the need for more action, new innovative concepts and globally suitable practices to boost our ability to reduce our influence on global climate change and help to lower these projections. The necessity to reduce our resource consumption, increase the
uptake of Renewable Energy Sources (RESs) and implement more sustainable practices is further highlighted by the Earth Overshoot Day metric [5]. This marks the date when humanity’s demand for ecological resources and services in a given year exceeds what Earth can regenerate in that year, which was first calculated to be the 30th of December in 1970 [5]. The clear and poignant evidence that human activities have created a negative impact is underlined by the equivalent overshoot day in 2021 falling on the 29th of July [5]. This evidence, combined with the fact that each of the last four decades have been successively warmer than any decade that preceded it since 1850 [1], ensures that change and new mitigation strategies must be implemented on local, regional, national and international scales around the world.

As three of the most influential governing bodies, largest economies and highest carbon emitters worldwide [6], China, the United States of America (USA), and the European Union (EU) can and should be international leaders when it comes to climate change. Particularly as according to the IPCC, droughts have become more frequent in much of continental East Asia and the rate of intensification and number of strong tropical cyclones have increased [7]. Mean and extreme high temperatures are expected to continue rising, ocean acidification and sea levels are projected to increase and strong declines in glaciers, permafrost and snow cover will continue in North and Central America due to climate change [8]. Similarly, mean temperatures, sea levels and the frequency and intensity of hot extremes and heatwaves are projected to continue to increase in the EU due to the impact of climate change [9]. This has forced these governing bodies to reassess and adjust their NDCs, pledging more ambitious and impactful long-term targets. The Chinese government have updated their initial NDC goals, at the highest level aiming to lower Carbon Dioxide (CO₂) emissions per unit of gross domestic product by over 65% compared to the 2005 level [10]. The USA, having re-joined the Paris Agreement have committed to achieving an economy-wide target of reducing its net Greenhouse Gas (GHG) emissions by 50-52% below 2005 levels in 2030 [11]. The EU and its member states have committed to the binding target of net domestic reduction of at least 55% in GHG emissions by 2030 compared to 1990 levels [12]. Certain member states can set their own goals and roadmaps to achieve their own and the wider group’s emission reduction targets. California for example is renowned as a leader in this area and has long standing commitments to its own goals to reduce GHG emissions to 40% below 1990 levels by 2030 and 80% below 1990 levels by 2050 [13]. Members of the EU, like Ireland for example, can also set their own national targets to achieve the required emission reductions. A key factor to achieving these targets in addition to reducing resource consumption and improving overall efficiencies, has been the
increased implementation and utilisation of RESs. As these are generally seen as clean, emission free sources of energy they can be pivotal to meeting emission reduction targets. However, the growing levels of variable and unpredictable RESs on national electricity grids, traditionally reliant on stable fossil fuel generation, can have a destabilising effect [14], which will create new challenges and require new innovative solutions in this area.

### 1.1.2 The Irish Perspective

The Republic of Ireland, as an EU member state, is committed to contributing to the overall EU emissions reduction target, with its contribution equating to a 30% reduction in GHG emissions compared to 2005 levels by 2030 [12][15]. Ireland did not meet its 2020 targets, more specifically failing to reach its target for RES to supply at least 16% of gross final energy consumption, with its actual share only accounting for 13.5% in 2020. Although the Irish target was jointly one of the most demanding 2020 targets allocated to an EU member state [16], this shortfall increases pressure on Ireland to advance its progress and get back on track to meet its updated contribution requirements. The national climate policy position establishes the government’s national objective of achieving a competitive, low-carbon, climate-resilient and environmentally sustainable economy by 2050. This outlines the policy driving factors and targets to achieve an aggregate reduction in CO\textsubscript{2} emissions and equivalent, of at least 80% across the electricity generation, built environment and transport sectors compared to 1990 levels by 2050 [17]. It also details an approach to carbon neutrality in the agriculture and land-use sector, which does not compromise sustainable food production. This long-term strategy is ingrained in Ireland’s ambition to achieve the 2030 GHG emission reduction of at least 30%. Two key aspects required to meet this goal are reaching at least 32.5% energy efficiency and delivering 70% renewable electricity [18]. This commitment to increase the electricity generated from RESs from 30 to 70% by 2030 [19], represents a significant change from current practices and will present numerous challenges. The Irish government is driving the increased uptake of RESs through several new support systems, broad funding programmes and specific incentive schemes to encourage and ensure the required implementation is achievable [19]. The continued proliferation of RESs, like onshore and offshore wind, will help to achieve the critical national emission targets, however additional systems and strategies will be required to minimise the destabilising effect of these RESs, particularly on the relatively small, islanded national electricity grid of Ireland.

The Irish national electricity grid is a single network for the entire island of Ireland, serving both the Republic of Ireland and Northern Ireland. This network is jointly overseen by EirGrid
and System Operator for Northern Ireland (SONI), as the Transmission System Operators (TSOs) for the Republic and Northern Ireland respectively [20]. The intended operating frequency of the Irish electricity grid is 50 Hz, with a normal operating range between 49.8 Hz and 50.2 Hz [21]. Both TSOs are responsible for maintaining the instantaneous balance of supply and demand to keep the frequency within this range and ensure reliable operation [20].

The Integrated Single Electricity Market (I-SEM) is the wholesale electricity market arrangement for the network, which went live on the 1st October 2018 to increase integration with European markets [22]. The I-SEM structure has allowed the TSOs to support the integration of more intermittent generation sources and implement more initiatives encouraging system interaction and flexibility. One such initiative, “Delivering a Secure, Sustainable Electricity System” (DS3), aims to meet Ireland’s electricity and emission targets by increasing the RESs on the system in a safe and secure manner [23]. Generally, the DS3 programme increases grid reliability and the controllability of higher levels of RESs through several interactive system services for participants to offer flexibility to the TSOs. The 14 DS3 system services can be split into a number of categories covering, system reserve, ramping, inertia, fast-acting response and reactive power [24]. Incentive payments are offered to encourage participation in these services, with fast frequency and primary operating reserve generally the most lucrative as they provide the most valuable resource to the TSOs [25]. To date the DS3 programme has enabled EirGrid to increase the levels of RESs on the system from 50 to 65%, helping to lower curtailment and increase the average share of RESs on the grid. This percentage limit is known as the System Non-Synchronous Penetration (SNSP) limit, which defines the instantaneous percentage of the generation mix that can be made up of RESs, interconnector capacity or other non-synchronous generation sources [26]. The SNSP limit defines the maximum amount of supply from RESs, like wind, that can safely be incorporated onto the grid by the TSOs at any time [26]. The overall goal of the DS3 programme is to maintain the correct structure, level and type of services to ensure the system is capable of securely and reliably operating at over 75% SNSP [23].

The Irish electricity network is a relatively small and isolated system compared to other larger more interconnected international grids. This presents unique challenges, particularly as individual generation units are typically large compared to total system demand [27] and universal issues concerning grid stabilisation are amplified compared to larger grids with more system inertia. This high single generator to system demand ratio means the grid is especially susceptible to reliability issues or even blackouts when large power stations encounter
unexpected downtime, refurbishments or repairs that delay their return to the generation mix [20][28]. Similar problems may occur as the national grid transitions away from traditionally stable fossil fuel generation plants to more RESs and Distributed Energy Resources (DERs) to meet emission reduction targets [20]. This is highlighted by the share of RESs in the Irish generation fuel mix increasing from 36% in 2019 to 43% in 2020 [29]. Achieving this figure was heavily influenced by the continued growth and importance of wind energy on the Irish grid. In 2020, wind generation accounted for 36.1% of all electricity generated, second only to natural gas as the largest source of energy [15]. This continued growth in 2020, meant wind provided 36.3% of the national electricity demand and even accounted for a larger share then natural gas in the first and last quarter of the year [30]. This percentage of wind energy represented the highest share of electricity demand met by onshore wind in the world, further highlighting the value but also considerable influence wind energy has on the Irish grid [30]. The continually growing share of wind energy, as Irelands most influential RES, compounds the need to increase the levels of flexible capacity available to the TSOs under strategies like the DS3 programme, which assist them to prevent network destabilisation and maintain reliable control of the electricity grid.

1.1.3 Maintaining Grid Reliability

The TSOs require a number of different tools and systems to maintain reliable control of energy networks, particularly to incorporate higher levels of RESs within the smart grid architecture. The smart grid concept is the theory that modern power grid infrastructures and electricity grid networks should incorporate advanced information and communication technologies to allow each component and participant to interact and influence the operation of the overall system [31]. This concept provides the TSOs with better visibility and more reactive and responsive control over electricity networks. An important element for the TSOs to maintain grid stability and potentially a core aspect of the smart electricity grids of the future is the availability of flexible capacity. System flexibility or having flexible capacity available allows the grid to react with available energy capacities to adequately respond and help to reduce any mismatch between grid supply and demand [32]. This can be defined as aggregated electrical capacity at the TSO level available to respond and provide system regulation and stabilisation without jeopardising the operational constraints of DERs or the source distribution networks [33]. The growing requirement for flexible capacity combined with the proliferation of DERs is leading to a more interactive and responsive grid, with many stakeholders employing a more “prosumer” approach to their energy systems [14]. This approach, where energy is both produced and
consumed onsite [34], means a prosumer can either produce their own electricity to supply the grid, consume their own self-generated electricity or consume only electricity from the grid. This flexibility on a user level creates more options for engaged stakeholders but also varies what the TSOs see on the grid level and therefore how they respond to grid events compared to traditional practices. Another element within the smart grid concept, to successfully integrate DERs and efficiently manage energy resources for smooth and continuous balancing of supply and demand is the practice of Demand Side Management (DSM) [35]. DSM is often defined as the governance of consumer energy demand through financial incentives and behavioural changes to influence their electricity consumption profiles to benefit the wider grid [35]. Demand Response (DR) is another practice renowned as an increasingly valuable tool to provide grid flexibility and assist the integration of higher levels of RESs [36]. DR is generally focused on load flexibility through temporary short to medium term load reductions, often classified as load shedding or load shifting strategies [36]. This helps shape normal electricity consumption patterns in response to grid requirements or, variations in electricity prices or to capture incentive revenues designed to minimise demand at times when system reliability is jeopardised [37]. Response schemes are often triggered by system frequency fluctuations or disturbances on the network called Grid Frequency Events (GFEs). In Ireland, a GFE occurs if the frequency falls below 49.7 Hz or rises above 50.3 Hz at any point [24], which would generally incite a response from DR participants.

There is considerable DR potential across all sectors globally, with some existing examples of individual or combined programmes evident across the residential, commercial and industrial sectors [38]. On the residential scale, there are examples of buildings providing flexibility through smart control systems. In this case, the building was designed to follow a designated power set point from the grid operator which would signal the appropriate acceleration or postponement of its space heating loads [39]. Outside of Ireland, examples of large aggregations of residential participation also exists, with the most developed instance of this being Community Choice Aggregations (CCAs). A CCA is generally a large group of residential energy users that combine to form a single aggregated consumer. In areas where DERs, like rooftop solar photovoltaics (PV) are common, they can even become prosumers for the local grid [40]. The DR potential of the commercial sector has also been extensively evaluated to uncover the potential of the buildings in this sector to reduce or shift electricity use to improve grid reliability. Studies have investigated shutting down commercially operated chillers to respond to fast DR events [41], the optimisation of commercial building heating
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systems [42] and the ability of specific commercial buildings to reduce peak demand under differing control strategies [43]. The potential for a commercial building to operate individually or as a contributor to a Virtual Power Plant (VPP) has also been investigated [44]. VPPs are a mechanism for controlling and managing an interconnected aggregation of assets, including but not limited to, DERs, energy storage and flexible loads, enabling them to participate in the market in the same manner as a conventional power plant [45][46]. A VPP presents a total capacity similar to that of a conventional power plant but appears to the TSO and market as a variable-size power plant. This further incorporates valuable flexibility into the grid, allowing DR contributors previously unable to engage with the grid the opportunity to participate. Finally, there is also potential for the industrial sector to participate in DR individually or to combine with other sectors as part of an aggregation or even contribute to a larger VPP. This potential is emphasised by the scale of the industrial sector, which accounted for 23% of the final electricity consumption in Ireland in 2020 [15]. Furthermore, the Large Industry Energy Network (LIEN), which represents almost 200 of Ireland’s largest industrial energy users, accounted for approximately 18% of Ireland’s total primary energy requirement, approximately 30,270 GWh, in the same year [47]. Based on these figures and comparable examples, further evaluation is required to uncover the DR potential present in this sector. However, as this is traditionally a highly regulated and risk averse sector, appropriately capturing this potential presents challenges.

1.1.4 Energy Flexibility in the Industrial Sector

As the industrial sector accounts for a considerable portion of national energy consumption, there would be substantial impact if flexible capacities were made available from this sector. Production equipment is often considered the main energy consumer in this sector and so opportunities for adaptive energy measures were reduced, with industries being reluctant to adjust operations or affect their critical assets. However, numerous ancillary services and utility assets may be suitable for DR aside from production equipment, as individual asset power consumption is generally higher in this sector [48]. Industrial assets like Air Handling Units (AHUs), compressors, chillers and large pumps or motors serving non-critical areas may all be suitable for DR. A defined framework would help to identify the flexibility of these assets and ensure the suitability of their participation in DR, although it would need to be appropriate for the highly standardised industrial sector. Beyond deciding which assets are suitable for DR and ensuring the rigor of this selection, assessing any risk associated with their participation would also be vital in this particularly risk averse sector. Incorporating elements of criticality ranking
1. Introduction

and risk rating, which are already common in this sector [49][50], would greatly benefit the rigour and confidence provided by any framework proposing assets for DR participation. Furthermore, reputable international standards, like those published by the International Organisation for Standardisation (ISO) and industry best practices are essential to assess perceived risk appropriately. These offer a robust foundation and standardised approach to evaluate and minimise any consequences of altering processes while also providing the confidence in results needed in this particularly risk averse sector.

Modelling is another useful aspect to assess certain processes that may be suitable for DR and can be particularly valuable to evaluate this potential. Modelling systems virtually allows evaluation of any potential risks before physical changes are implemented or any practical work is commenced. Some investigation of modelling industrial assets has been conducted, like evaluations of Combined Heat and Power (CHP) units [51] and AHU loads specifically to reduce peak demand during peak times [52]. Other studies have evaluated synergies between Heating, Ventilation and Air Conditioning (HVAC) load and manufacturing heat sources to reduce peak demand [52] and another study explored passive measures to prevent overheating in an industrial building [53]. Mechanically ventilated offices in the industrial sector however have received less attention, particularly on sites where production is the primary function, but offices still account for a large area of the facility. These industrial buildings, characterised as large, low complexity, prefabricated shells, are typically classified as very light to medium internal thermal storage capacity by standards like ISO 52016-1 [54]. This highlights the energy performance of these buildings, their energy needs for heating and cooling, internal temperatures and both sensible and latent heat loads. Although both the thermo-physical characteristics of these industrial offices and make up of their AHUs are not directly comparable to their custom-built commercial counterparts, they are governed by the same requirements. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) publish a prominent standard on these conditions, ASHRAE Standard 55 - Thermal Environmental Conditions for Human Occupancy [55]. While the ISO, among others, also present guidelines and recommendations providing structure to assess these conditions, captured in ISO 7730 [56]. Capturing AHU and building thermal response dynamics is a challenge to model potential flexibility effectively and with acceptable accuracy. Research has been conducted in the commercial sector and modelling of internal temperature conditions in naturally ventilated offices [57][58], however it would be valuable to investigate other systems common in the industrial sector. It would be particularly valuable for evaluations
to account for the risk averse and strong validation culture on large industrial sites when evaluating the potential DR capabilities.

1.2 Research Objectives

To maintain the reliability of national electricity grids as the levels of RESs continue to increase to meet emission reduction targets, it is imperative that TSOs are provided with the necessary levels of flexible capacity to balance supply and demand. An area identified as having large electrical capacities and considerable potential to provide this is the industrial sector, where additional DR participation may offer the TSOs some of the required flexibility. This presents challenges, as the highly regulated industrial sector has traditionally been risk averse with its assets to safeguard production output. There are numerous opportunities and non-production assets on an industrial site however, that may be suitable at very low-risk levels for the participant. To capture this potential and provide the flexible capacity levels required by the electricity grid, further evaluation and new demonstrations of the capabilities and low-risk capacities achievable are needed to encourage participation from this sector.

The overarching aim of this thesis and the research it presents is to advance the practical engagement and participation of the industrial sector in national DR programmes, through the development of an appropriate decision-support framework and risk-assessment modelling tool to illustrate the potential available and impact it may represent. To further this topic, it is important to present the advantages and prohibiting factors in a suitable light, relevant to the appropriate participants in this sector, to encourage new and continued engagement and provide decision support for key stakeholders. A novel framework suitable for this sector is needed, to reduce the complexity and support the decision-making and engagement process for relevant participants completely new to this topic. This defined framework must capture all aspects necessary to ensure the success and sustainability of their participation in the industrial sector. Furthermore, a new and appropriate risk-assessment modelling tool is required to minimise the perceived risk of DR participation and clearly demonstrate the suitability of identified assets. Modelling certain elements that influence the risk associated with their participation is important to reassure their selection and safe inclusion in an industrial DR portfolio. Based on this new research, the benefits to a site and their potential influence on a national grid level should be quantified, to demonstrate the considerable positive impact achievable and encourage continued advancements and further implementations in this specific area. The core Research Objectives (ROs) of this thesis, to satisfy these requirements are defined as follows:
RO1. Assess and critically appraise the predominant benefits, driving factors and barriers to industrial engagement and participation in national electricity grids.

RO2. Investigate and formalise a prescriptive framework to advance industrial participation in DR schemes and provide decision support to inform and encourage additional industrial participants.

RO3. Develop a suitable risk-assessment modelling tool to evaluate and demonstrate elements that influence the operational risk of a suitable industrial asset participating in DR to minimise the perceived risk and encourage further participation in the industrial sector.

RO4. Quantify and highlight the potential benefits of selected industrial assets deemed as low risk being incorporated into DR programmes and illustrate their potential impact on the Irish national electricity grid.

1.3 Thesis Structure

The remaining chapters of this thesis are outlined as follows, illustrated in Figure 1:

- **Chapter 2** presents a comprehensive review of published literature relevant to the research undertaken in this field. This chapter outlines the leading and most influential concepts, current best practices and integral methodologies and approaches. Specific details on industrial smart grids and DR are presented, including the predominant benefits, driving factors and barriers of these concepts. The sector specifics from relevant case studies and comparable examples are also presented in detail to provide a clear understanding of the research area.

- **Chapter 3** outlines the development of the systematic framework that forms the basis of this thesis. Detailing the prescriptive process steps, incorporated risk assessment techniques and modelling approach that aims to address the knowledge gap in this area and fulfil the research objectives.

- **Chapter 4** describes the implementation of the proposed framework on a representative case study industrial site. This outlines the application of the asset identification, categorisation and risk assessment steps including the utilisation of the proposed modelling approach. The specific case study building thermal characteristics and relevant calculations are highlighted, including the sensor placement and the empirical data collection process, the calibration and validation techniques applied, model
statistical and sensitivity analysis and the compilation of weather and boundary conditions to support the results of this study.

- **Chapter 5** details the overall findings and results of this thesis. The outputs from implementing the presented framework are outlined and discussed. The modelling scenarios and results of the analysis are illustrated, exploring any potential impacts of relevance and presenting important insights to enhance the value of this demonstration for potential industrial participants. Finally, the scalability and potential impact of this research on a site and national grid level is illustrated and discussed.

- **Chapter 6** provides a summary and offers concise conclusions of this research and its results. The specific contributions of this thesis and a critical appraisal of this work and its limitations are outlined, in addition to suggestions for future work derived from this research.

*Figure 1. Overview of thesis chapters and research objectives to be addressed.*
1.4 Summary of Contributions and Novelty

This section outlines the specific contributions of this thesis and the novelty of this research, including its value to the industrial sector and the wider research area. The general contribution of this thesis is to advance the understanding of industrial participation in DR, with the intention of encouraging additional engagement and participation on a national scale. The core and specific contributions are defined as follows:

- A new critical review and appraisal of the benefits, driving factors and barriers of the industrial smart grid and DR concepts, highlighting the key aspects influencing industrial engagement and participation in national electricity grids.
  - Further, the integral and influential concepts within this research area are also critically assessed to develop this area further and provide a strong foundation for future research in this area.

- A novel framework to confidently identify, categorise and select assets on an industrial site for participation in national DR programmes, presenting their suitability and associated levels of risk following a new risk-assessment methodology as part of the decision-support framework.
  - In addition, this thesis details its implementation on a relevant industrial case study site. Thus, providing a clear demonstration and practical example for decision makers, assisting them to implement this framework on their own industrial site and achieve the associated benefits outlined.

- A new, easily scalable and transferable risk-assessment modelling tool tailored to thermally light buildings that are representative of office spaces on industrial sites, for the novel application of quantifying any operational risk to the indoor thermal environment served by the AHU caused by its participation in a national DR programme.
  - This modelling approach can be viewed as a standalone risk-assessment modelling tool for evaluating thermal environments served by industrial AHUs participating in DR or as part of a comprehensive risk-assessment on an industrial site as outlined in this thesis.

- A novel quantification of the potential flexible capacities available from representative groupings within the Irish industrial sector and original illustration of the potential impact they may have on the national electricity grid.
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- The demonstration of the value to an individual site or even local coordinated participants offers an example of the financial value achievable, which may help to encourage decision makers and increase national levels of industrial participation in DR.
- The potential flexible capacities outlined in this thesis highlight the value to the national grid that could be achieved through the further engagement and participation of the industrial sector in this concept. This may encourage additional funding or incentive schemes from TSOs or the relevant governmental departments to make this a reality.

1.5 Publications

The following publications represent the primary dissemination of the research contained within this thesis:

**Journal Articles**

Relevant Co-Authored Works

Chapter 2

Literature Review

2.1 Introduction

This chapter is intended to introduce and provide context of the broad industrial smart grid and industrial DR research areas, give the reader a clear understanding of specific terminologies and present a critical review of published literature to position this research within the wider research area. The objective of this review is to highlight current best practices and existing examples as well as present a background to the theory and concepts mentioned in this thesis and the research it builds upon. Section 2.2 presents a review of the relevant literature, concepts and technologies in the industrial smart grid and industrial DR research area as shown in Figure 2, implementing the systematic mapping methodology, which is detailed in Section 2.2.1.1. Sections 2.2.1 and 2.2.2 present two separate systematic mapping studies that outline the relevant aspects of both the industrial smart grid and industrial DR concepts. A general overview of these concepts within their relevant research areas are presented in addition to their specific benefits, driving factors and barriers to adoption and successful implementation.

Figure 2. Flowchart of Literature Review, outlining hybrid systematic approach and hierarchy of topics.

Section 2.2.3 provides clear definitions of area specific terminologies and niche concepts, outlines suitable examples and relevant studies in detail as well as illustrating potential learnings from other representative implementations or sectors. Section 2.3 outlines a review of influential methodologies and approaches in the literature for asset selection, risk assessment
and modelling internal air temperature, relevant for DR applications and implementation in the risk averse industrial sector. Finally, Section 2.4 presents the conclusions of the literature review, highlighting the overall findings from specifically relevant studies and the potential research required to fill identified knowledge gaps and to benefit the wider community as a whole.

2.1.1 Background
The security and reliability of national electricity grids is an ever-present concern and important aspect to maintain a daily, uninterrupted supply of electricity to all users while avoiding major frequency fluctuations or even blackouts. Historically, national electricity grids were heavily reliant on large fossil fuel generation plants for baseload demand or carbon emission heavy peak generation plants for grid regulation [20]. These traditionally unidirectional, cascading electricity grid networks, as demonstrated in Figure 3, were particularly carbon intensive and lacked the required communication capabilities to sustain the grid as more variable energy sources were brought onto the grid. As environmental and policy factors have driven change in the energy sector, these traditional grid architectures have been forced to adapt. This is particularly evident in Ireland, where a historically large generator to peak demand ratio and a relatively small and isolated grid network with minimal communication capabilities has led to low grid flexibility. This lack of flexibility can cause challenging conditions for the TSOs to maintain reliable control of the grid, which can become particularly vulnerable if critical plant outputs fluctuate or suddenly drop out of the generation mix.

![Diagram of a traditional, cascading one-way flow electricity grid architecture](image)

*Figure 3. Low complexity overview diagram of a traditional, cascading one-way flow electricity grid architecture [59].*
National and international emission reduction targets and policies have driven the proliferation of RESs and the decommissioning of older, less efficient fossil fuel plants from the generation portfolio [20]. As a result, a more dynamic, interactive and communicative grid architecture is required to control this developing electricity system and ensure uninterrupted supply is maintained. The smart grid concept offers a solution to these growing issues, providing the communication structures required for a more interactive and responsive electricity grid that can suitably assist the TSO to maintain stability as levels of RESs, like wind, increase their influence in the generation mix. These dynamic responses and network stability measures required by the TSO will continue to grow in value and will need to be sourced from a variety of energy producers and consumers to ensure the continued availability of suitable capacities. The industrial sector, highlighted as a large consumer of energy with influence in this area [15][47], shows potential to offer considerable benefit [60], however the concept, possible opportunities available and means to achieve this requires additional definition and further investigation.

2.1.2 Research Objectives

To evaluate and fully understand a research area it is important to uncover and critically appraise the benefits it can provide, the driving factors for progression and the barriers or reasons behind its slowed adoption, if any are present, to identify potential avenues for further development [61]. Conducting a critical review of the relevant literature in the specific area is vital to doing this as previous examples and case studies highlight each of these factors. Gaining a thorough understanding of these aspects can help to identify avenues for future work, required to overcome specific barriers that can provide considerable benefit to the research topic [62]. Furthermore, building upon useful experience and learning from previous examples can help to develop future work successfully, avoiding the potential pitfalls of previous research. The intention of this chapter therefore, is to appraise existing research critically to identify and outline the predominant benefits, driving factors and barriers of the industrial smart grid and industrial DR concepts. This will add further detail and provide a new, deeper understanding of the research area in line with RO1, while also increasing the value of this thesis and building a strong foundation for this research.

**RO1.** Assess and critically appraise the predominant benefits, driving factors and barriers to industrial engagement and participation in national electricity grids.
2. Literature Review

2.2 Review of Key Concepts and Technologies

This section presents a critical review of the literature relevant to the industrial smart grid and DR concepts based on the defined systematic mapping methodology. Each concept will be evaluated to provide a detailed overview and offer insights into the relevant benefits, driving factors and barriers that have influenced implementation and adoption of these topics. Providing further clarity of these aspects will help to identify research gaps and potential avenues for development and improvement that can offer value to future research in this area. The integral and influential concepts within this research area, uncovered during this analysis, will also be discussed further to fully capture this research topic and outline any additional knowledge or experience that may be valuable to future projects or implementations of these concepts. This will help to ensure the relevance of this work and maximise the potential impact of the research presented in this thesis.

2.2.1 The Industrial Smart Grid Concept

The smart grid concept is the theory that modern power grid infrastructures and electricity grid networks should incorporate advanced information and communication technologies allowing each component and participant to interact and influence the operation of the overall system [62][63]. The conventional or traditional grid architecture operated generally as a one way system, where energy flowed from power plants to consumers with minimal interaction [31]. The smart grid concept paves the way for a more interactive and responsive grid through two way data flow between supply and demand sides using smart, integrated communication technologies [64]. This transition is closely aligned with the continued integration of DERs and the proliferation of RESs on electricity grids worldwide, meaning TSOs are required to observe additional information and maintain tighter, more responsive control of the network. The evolution from conventional, large fossil fuel powered generation plants towards more dispersed DERs and variable RESs to meet emissions targets is continuing to add more variables and complexity to the grid on the supply and demand side [20][65]. To facilitate the collection and processing of these additional data sources, technologies like smart sensors, advanced automatic control and monitoring equipment and innovative scientific management methods are required [63]. Within the industrial sector, smart meters, intelligent power generation and storage systems are vital to ensuring the precise control and management of electrical operations. These smart technologies offer the industrial electricity consumer more visibility and control of their usage and provide them with the opportunity to engage and interact with the smart grid. A general overview of the system architecture and potential factors,
2. Literature Review

inputs, outputs and communication links in a smart grid serving an industrial customer is illustrated in Figure 4. This demonstrates how integral this concept can be to a site's electrical usage and its valuable influence on the efficient and reliable operation of numerous aspects of the system. As outlined, each domain is connected and able to communicate with the other system components through dedicated gate- and path-ways. This is vital, as in order for the TSO to maintain the instantaneous balance of supply and demand required, it must constantly be aware of availability on both sides of the grid and other monitored factors like grid frequency [21]. This allows the TSO to control generator output to maintain supply or to signal dispatchable resources or DR participants into action to counteract fluctuations in the grid from the demand side. This ability afforded to the TSO is a key aspect of the smart grid concept, as the two-way communication and ability to correct frequency fluctuations from the demand side greatly enhance the controllability and overall reliability of the electricity grid network.

![Figure 4. General overview of the industrial smart grid concept and system architecture [66].](image)

2.2.1.1 Literature Review Methodology

Many different approaches and methodologies for conducting literature reviews have previously been utilised, namely narrative, meta-analysis, semi-systematic and systematic reviews [61]. A narrative review provides a selective and broad review of a specific topic, which does not follow a strict method to select and synthesise the literature and therefore may incorporate bias. Meta-analysis reviews follow a more systematic approach, quantitatively combining the results of selected studies and allowing for statistical analysis of the pooled results of the chosen studies. Systematic reviews utilise exacting search strategies to ensure the
maximum extent of relevant research articles are considered, methodically appraised and synthesised. Systematic approaches have been referred to as the gold standard for conducting literature reviews and generally provide a structured method to efficiently identify research papers and appraise an entire defined research area critically [61]. The systematic mapping process is a methodology designed to give an overview of a research area through classification and compilation of contributions in relation to the defined categories of that classification [67]. Following this method of efficiently searching through the relevant literature, it is possible to create a comprehensive and fully documented evaluation of the current state of the art of a research topic, including identification of what aspects have been covered and where it has been published. This structured approach to synthesising the information of a research topic allows for detailed analysis of a broad area with clearly defined outputs and informative illustrations [62]. Systematic mapping, or scoping studies, are comparable to the systematic review process in terms of searching and study selection however, their goals are different and so their approach to data analysis is different [67]. Systematic reviews aim at synthesising evidence and considering the strength of this evidence, whereas systematic mapping studies are primarily concerned with structuring a research area and comprehensively presenting it for further analysis. The systematic mapping process was chosen as the methodology to conduct this literature review as it provides a rigorous protocol to identify and capture all relevant papers in a research field to evaluate and capture for further analysis. This allows the overall research area to be reviewed and provides a platform, and repository of relevant research papers, to build upon and conduct further analysis and a more thorough and detailed review of specific aspects of the relevant literature. The systematic mapping process follows a defined and structured approach made up of three distinct phases, planning, conducting and reporting as outlined in Figure 5.

Figure 5. Process flow diagram of systematic mapping methodology.

The planning phase consists of defining the scope and ensuring the aim of the study is suitably focused. Formalising the research questions from the outset ensures that the motivation and
2. Literature Review

The purpose of the study is well described and the proceeding processes are based on an appropriately defined structure. The conducting phase implements the specific mapping methodology and planned processes, ensuring a comprehensive collection of relevant papers are captured and maintaining a detailed recording of information through each process step. Creating an all-encompassing and well described research paper repository is a key aspect of this methodology and the care taken at this step can be key to the overall value generation and successful implementation of the mapping methodology [62]. It is vital to capture as many relevant papers as possible during the initial search step to maximise the effectiveness of this methodology and ensure a comprehensive overview of the research area is presented. This is achieved by entering defined search terms into scientific research paper databases, ensuring the terms are specific enough to maintain the efficiency of this method yet suitably broad to capture all aspects of the topic. Fully documenting this step ensures the structure and repeatability of this process. Once the search for papers is complete and the relevant papers compiled into the repository the screening phases can begin. During the first screening phase the title and abstract of each paper is evaluated to eliminate any unsuitable papers, for example papers no longer deemed relevant after this evaluation, duplicates or papers without full-text availability. The publication data of each qualifying paper is then collected and tabulated within the repository under the appropriate headings. The second screening phase evaluates each qualifying paper in more detail, assessing the title, abstract, results and conclusions of each paper, further determining the relevance and valuable contribution of each paper at this phase. The papers still deemed relevant after this phase have a number of additional categorisation details, including data information and research classifications, added to the repository to supplement the existing publication date captured in the repository. The reporting phase consists of evaluating the results and findings to suitably answer the research questions and provide a detailed description and overview of the specific topic. This allows relevant discussion points and conclusions appropriate to the research area to be drawn and included in any compiled reports or final outputs of this systematic mapping process. The systematic mapping process was utilised as the methodology to outline and investigate the industrial smart grid and industrial DR concepts in the following sections. This allowed for further analysis of these topics, as outlined in RO1, in addition to compiling a repository of relevant research papers that are also reviewed throughout this chapter.
2. Literature Review

2.2.1.2 Systematic Mapping Overview of the Industrial Smart Grid Research Area

Following the systematic mapping methodology outlined in Section 2.2.1.1, the scope of this individual study was defined as literature specifically related to the industrial smart grid research area. The research questions were also defined as assessing and critically appraising the predominant benefits, driving factors and barriers to industrial participation, in line with RO1 to complete the planning phase of this process. To complete the conducting phase of this process, the repository was created to store the results before the initial search was performed, where research papers were identified from the databases and using the search terms described in Table 1. Of the initial 483 papers identified using the systematic mapping process, 337 were excluded during the first screening phase and 32 further papers were excluded during the second, more detailed screening phase. Upon completion of the systematic mapping process on the topic of industrial smart grid systems, where the term industrial micro grid was also found to be used interchangeably in some studies, 114 specifically relevant papers were identified for further review and analysis in this area. Following the defined process, these papers were evaluated and analysed to provide an overview of the research area and compile the results with the intention of answering the research questions concerned with the benefits, driving factors and barriers associated with this specific concept.

Table 1. Overview of the databases and search terms used to identify relevant papers during the systematic mapping process of the industrial smart grid concept.

<table>
<thead>
<tr>
<th>Database</th>
<th>Search Area</th>
<th>Search Terms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 IEEE Explore</td>
<td>Document Title</td>
<td>Industrial Smart Grid OR Industrial Micro Grid</td>
</tr>
<tr>
<td>2 IEEE Explore</td>
<td>Metadata Only</td>
<td>&quot;Industrial Smart Grid&quot; OR &quot;Industrial Micro Grid&quot;</td>
</tr>
<tr>
<td>3 Science Direct</td>
<td>Full Text</td>
<td>&quot;Industrial Smart Grid&quot; OR &quot;Industrial Micro Grid&quot;</td>
</tr>
<tr>
<td>4 Science Direct</td>
<td>Title</td>
<td>Industrial Smart Grid OR Industrial Micro Grid</td>
</tr>
<tr>
<td>5 Scopus</td>
<td>All Fields</td>
<td>&quot;Industrial Smart Grid&quot; OR &quot;Industrial Micro Grid&quot;</td>
</tr>
<tr>
<td>6 Scopus</td>
<td>Title-Abs-Keywords</td>
<td>Industrial Smart Grid OR Industrial Micro Grid</td>
</tr>
<tr>
<td>7 Google Scholar</td>
<td>Exact phrase, anywhere in the article, not including patents or citations</td>
<td>&quot;Industrial Smart Grid&quot; OR &quot;Industrial Micro Grid&quot;</td>
</tr>
</tbody>
</table>

These 114 identified papers on the topic of industrial smart and micro grid systems were evenly split between conference and journal publications with 57 of each captured in the research paper repository. The earliest identified paper was published in 2010, with the remaining papers published as outlined in Figure 6. This timeline of publications demonstrates the evolution of this specific research area, from the first publication in 2010 and its development over the
following years. The continued increase in publications until 2016 highlights the growing interest and particular focus on this research topic, which culminated in a peak of publications in 2017 and has remained between 12 and 16 since then. The plateauing of growth in overall publications and timing of journal publications overtaking conference publications may indicate that this research area is beginning to mature. As this happens, new research builds on existing works to further these studies and fill research gaps highlighted or left open by their predecessors. This is most clearly evident by the earliest journal paper in this specific area [68], which was published in 2012 being cited in several of the subsequent published studies. The number of annual publications on this topic may not change drastically as the research field continues to develop in the future. Generally, the research focus will progress towards more niche areas within the same topic or advancements in the area pushing it forward until new terminologies or definitions begin to overtake the original concepts. The smart grid however, is a considerably large and fluid concept with numerous sub topics, including DR and VPPs, that is likely to remain particularly relevant throughout the coming years.

The widespread geographical distribution of publications in this research area clearly demonstrates its universal applicability and global relevance. Of the identified publications, almost every continent was represented with some level of contribution as displayed in Figure 7. The main contributors were China with 23 and Germany with 14 publications; however, Iran and the USA also contributed a number of research outputs, with 9 and 8 publications respectively. The significant contributions from China, Germany and the USA are not
surprising as these countries are generally at the top of research output charts. This is further demonstrated by these three countries featuring in the top three standings of the Nature Index for research outputs in 2020/21 [69] and top four rankings for science and engineering articles published in peer-reviewed journals in 2018, according to the U.S. National Science Foundation [70]. In recent years, the leading institution for research outputs in this area in China is the North China Electric Power University, located in Beijing and Baoding. In Germany, the Fraunhofer Institute for Manufacturing Engineering and Automation located in Stuttgart and part of the wider Fraunhofer group has been the most active in this research area. Finally, in the USA, the University of California has demonstrated the highest output in this research area, with contributions from Riverside, Los Angeles and the Lawrence Berkeley National Laboratory. The research output from Iran is perhaps the most unexpected, due to their lower comparative ranking on the international research output charts. Nevertheless, particular interest in this research area has been demonstrated, with contributions largely coming from the Islamic Azad University in Tehran and the University of Isfahan, which is widely regarded as the most industrial city in Iran. From this categorisation of global publications, it is clear that there is an academic interest in the smart grid research area, which is also being strongly influenced by an industrial perspective and desire to drive research in this area forward [62].

![Geographical distribution of papers published in the industrial smart grid research area.](image)
2.2.1.3 Benefits & Driving Factors of the Concept

Following a review of the relevant literature, several specific benefits, advantages and driving factors of the industrial smart grid concept were highlighted during the reporting phase [62]. The first and most frequently occurring benefit of this concept is the documented ability to integrate and facilitate higher levels of RESs and DERs on the current electricity grids. A substantial and well documented challenge associated with these renewables and dispersed generation assets is their highly unpredictable and destabilising nature [71]. The considerable fluctuations that occur within electricity networks due to wind and solar PV are well known and discussed throughout the literature in this research area [72][73]. The ability of smart grids to facilitate grid interaction and advance response techniques, such as DR, can greatly improve the quality and reliability of major electrical grids [74]. This was particularly evident through a case study evaluating the reliability parameters of an industrial micro grid implementing procedures to maintain grid stability [71]. In this case, the evaluated case study site improved each year across each of the reliability metrics assessed with the inclusion of smart grid enabled DERs. Most notably reducing the reliability metric, energy expected not served, from 6.6 MWh in the first year down to 3.1 MWh in the fourth year of analysis in this grid stability study considering renewables and load growth [71]. Furthermore, a study investigating the impact of interactions with the electricity grid, enabled by smart grid technologies and systems, indicated that this practice can have a positive impact on electricity markets influenced by wind energy [72]. The magnitude of this impact is dependent on the levels of engagement and wind penetration on the system however, meaning the 4 to 9% cost savings presented in this study are system specific. These technologies and the smart grid concept can also be pivotal to the incorporation and full utilisation of Energy Storage Systems (ESSs), like batteries [75], flywheels [76] and even pumped hydro storage [77]. The smart grid architecture allows for more streamlined incorporation of these assets and can maximise their ability to provide valuable resources to the grid like frequency response, load shifting and other ancillary services [78]. Throughout the literature, this concept continually proves its worth to industrial energy networks, displaying improved stability and confidence in smarter grid systems [68].

Security of supply is another particularly evident benefit that frequently appears in publications and stands out as a crucial advantage of this concept within the industrial sector. Largely influenced by emission reduction targets and the current aging electrical grid infrastructure coming under increasing pressure creating a risk of potential blackouts [20], many large companies or industrial estates are moving towards securing their own electrical supply. This
is often in the form of one or multiple RESs or DERs providing energy for the specific facilities, which is generally facilitated by smart technologies onsite [51]. In this study, an industrial site implementing DERs enabled by its smart grid architecture is able to ensure its reliable energy supply, while also reducing daily electricity costs by 58% with one and up to 69% with two of its DERs. Maintaining these generation assets onsite increases the reliability and security of electrical supply to the site and even in the most extreme cases allows them to remain operational during times of exceptional grid strain or even power outages [68]. The capability to operate in islanded-mode for some industrial micro grid systems enabled by the smart grid concept can further strengthen their supply and potentially even eliminate the need for a grid connection [79]. This particular study however, outlines that operating in islanded mode is considerably more costly, as all energy demand must be satisfied onsite, costing the case study site $32,118 rather than $18,670 operating under normal conditions. The actual value generation of this sub-concept would be demonstrated in practice if the wider grid supplying the site were to encounter issues that may affect the site adversely. This is particularly relevant in large industries where having their own controllable supply allows them to further control and manage their consumption, allowing them to strive for class leading performance and the highest level of performance [80].

This concept can also alleviate some of the issues and challenges caused by the transition towards cleaner, more electrified transport [81]. This study evaluates the impact of electric vehicle charging points being integrated onto an electrical grid, demonstrating that they can be significantly more cost effective when coupled with solar generation. This study shows that the smart grid concept can facilitate these emerging technologies; however, it does not address the challenges created for the grid through this practice. It is clear that as electric vehicle adoption rises and more charge points are installed on the network, additional research and infrastructure solutions will be required to accommodate them seamlessly. Industries are being incentivised and further encouraged to incorporate more electric vehicles into their workforce commuter pool and provide more charge points onsite [82]. This can introduce additional challenges to the network, which a smart grid system can help to nullify by reinforcing the grid infrastructure and allowing for more communication, engagement and responsiveness within the network [83]. Further support through smart frequency control and effective voltage regulation, facilitated within smart grids are required to combat the adverse effects of significant electric vehicle uptake and use within the industrial setting to achieve the maximum benefit of this technology.
An additional benefit of the smart grid concept, complimented by their ability to increase the utilisation of RESs is their assistance in reducing GHG emissions of both individual industrial sites and the wider national grids [84]. Smart grid systems and their intrinsic technologies allow industrial energy users and networks to further incorporate cleaner energy production sources and reduce their dependence on fossil fuels [74]. This characteristic is particularly beneficial for industrial sites working to meet national and international emission reduction targets and aiming to comply with strict energy performance targets. For many industries, minimising their emissions can drastically improve their green image and corporate social responsibility, which can improve their marketability and give them a competitive edge in addition to avoiding fines for missing reduction targets and increased costs incurred for carbon taxes [85]. This study demonstrates a 57% reduction of expected annual carbon emissions and 59% reduction in associated carbon taxes compared to the normal operation of the analysed site. This demonstrates the value of incorporating additional RESs into a smart grid system, however the case study comparison is based on a specific grid make up and so the significance of the reductions must be taken as system specific. Government legislation and emission targets have previously and will continue to have a large impact on this topic. Due to the large impact the industrial sector can have on national emissions performance, accounting for almost 3,810 ktCO₂ or 12% of primary energy related CO₂ emissions in Ireland in 2020 [15], this sector can be influential in achieving the benefits from this concept. Significant pressure will be put on decision makers in this area to reduce their impact and help achieve national reduction targets, which the smart grid concept can and is helping to achieve. This is certainly the case in Ireland, with industrial facilities adopting these technologies and systems with the goal of maximising their existing resources, incorporating further RESs and reducing their emissions [51]. In this case study, an industrial site demonstrates the capability to reduce its electricity related carbon emissions by up to 88% over a 24-hour period using its onsite RESs facilitated by the smart grid control systems.

Energy performance targets and emissions policies are being revised and updated annually, becoming stricter each year, meaning industries will be forced to maintain continual improvements and operational changes. These challenging new legislations will continue to encourage industries to innovate and search for new solutions and methods to keep up with this progression and maintain the most value from their existing assets [86]. In addition to achieving compliance to current regulations through the benefits offered by the smart grid concept, industries will always attempt to optimise the cost effectiveness of their assets and overall
operation. One such example in the literature demonstrates the capabilities of an industrial site to achieve approximately 16% energy savings through smart grid enabled load scheduling [87]. Smart grid systems offer considerable potential to optimise internal energy management and reduce operational costs for industrial facilities [51]. The added value and driving factor of the smart grid concept are the lucrative incentive structures and payments associated with its adoption and continued implementation [64][88]. Engaging in grid system services, enabled by the smart technologies and methodologies also offer a lucrative revenue stream for industrial participants [89]. The financial gains and potential revenue stream associated with the smart grid concept is a particularly relevant driving factor in the highly competitive and value driven industrial sector. The dual benefit of reducing energy consumption and receiving payments for offering this capacity reduction is an enormous advantage of the opportunities provided through smart grid systems. In one case study, an industrial site demonstrates a reduction of its electricity cost by almost 14% simply by shifting its energy consumption from peak to off peak times, enabled by smart communications and control systems [90]. Continual advancements in smart and micro grid management-systems can provide further potential beyond the examples summarised in Table 2. Offering additional opportunities for industrial facilities to optimise their energy performance, maximise the impact of RESs and minimise their energy costs and carbon emissions, further providing financial benefits and cost savings [91].

Table 2. Summary of benefits achievable through smart grid technologies outlined in the literature.

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Figures</th>
<th>Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smart Grid practices improve the reliability and stability of electrical grids.</td>
<td>Reducing reliability metric of energy expected not served, from 6.6 MWh in the first year down to 3.1 MWh in the fourth year of analysis.</td>
<td>[71]</td>
</tr>
<tr>
<td>Smart Grid technologies assist the facilitation of additional RESs and DERs.</td>
<td>Increased security of supply and daily cost reductions of 58% with one and up to 69% with two DERs that could not have been incorporated without the smart grid.</td>
<td>[51]</td>
</tr>
<tr>
<td>Improve ability to minimise or avoid carbon emissions.</td>
<td>Demonstrated a 57% reduction of expected annual carbon emissions and 59% reduction in carbon taxes compared to non-smart grid enabled site operation.</td>
<td>[85]</td>
</tr>
<tr>
<td>Facilitate additional RESs to minimise site carbon emissions.</td>
<td>Illustration of a site’s ability to reduce its electricity related carbon emissions by up to 88% over a 24-hour period utilising its smart grid control system.</td>
<td>[51]</td>
</tr>
<tr>
<td>Provision of new smart grid practices and energy efficient operations.</td>
<td>A studied industrial site was capable of achieving 16% energy savings through smart grid enabled load scheduling.</td>
<td>[87]</td>
</tr>
<tr>
<td>Smart grid enabled energy efficiency measures provide opportunities for financial incentive payments.</td>
<td>Demonstrated reduction of 14% electricity costs on an industrial site by shifting its energy consumption from peak to off peak times, enabled by smart communications and control systems.</td>
<td>[90]</td>
</tr>
</tbody>
</table>
2. Literature Review

2.2.1.4 Barriers to Adoption & Implementation

During the reporting phase of the defined systematic mapping process several distinct barriers to the adoption and implementation of this concept were identified that would benefit from further research and evaluation. With all new concepts and innovative ideas there can be reservations to their initial implementation and delayed uptake due to a lack of understanding. The smart grid concept was no different with a particular barrier to its early adoption and implementation being an absence of clarity and lack of understanding of the topic [92]. This caused a number of stakeholders and potential early engagers to harbour reservations and be slow to commit to this concept. A survey of representative stakeholders in Norway confirmed this statement in addition to indicating that at the time of the survey, in 2012, as the concept was emerging there was no accepted definition of the meaning of “Smart Grid” [93]. For pioneering technological advancements and fundamental changes to the established way of doing things, a lack of clarity and clear definition can significantly hinder progress and create a barrier to its successful implementation. In the case of the smart grid concept, defined reviews outlining concept specifics, including technologies and systems [38], and demonstrated case studies outlining proposed implementations [94] have somewhat clarified the uncertainty in this area. Further studies have attempted to bridge the gap of data and information gathering to assist smart grid implementation [95], however this particular study only presents speculative outcomes without the practical results to convince reluctant potential participants. Additional publications have helped to increase the body of knowledge on this topic and begun to build confidence to transcend the initial barrier to adoption. Nevertheless, to fully overcome this barrier and encourage future implementations of this concept, defined and systematic procedures and frameworks, appropriate for the risk averse industrial sector are required to ensure the success of future implementations of this concept.

It is common for emerging concepts and topics to be delayed by a lack of suitable hardware or the need to upgrade existing infrastructures. The electric grid and several integral hardware devices on industrial sites were decisive factors in the early adoption of this concept. The need to improve and replace these hardware and software systems caused initial delays, particularly to confirm the requirements and suitably justify their installation in the risk averse and highly regulated industrial sector [75], which slowed the rate of developments in this area and would have benefitted from an efficient, defined risk assessment and evaluation framework. An example of a major material update in this area was the impact of power semiconductor devices
and their improvement trajectory in supporting aspects like increased voltage, frequency and temperature limits [96]. The availability of adequate control systems was also a considerable barrier to the widespread adoption of high-grade smart grid systems. Before the emergence of higher quality processors, smart communication devices and cloud-based applications it was considerably more difficult to implement these systems. The improvement and further advancement of the required infrastructures to incorporate and connect controllable local systems to external entities greatly increased the controllability and operational barriers to industrial grid systems [97]. Although this particular study is only focused on the German electrical grid, it does offer demonstrations of communications architecture universal to smart grid implementations. A lack of existing infrastructure and the cost of retrofitting or installing the required smart systems was originally seen as a barrier to early phase adoption in the literature. The smart technologies, such as advanced sensors, meters and monitoring equipment capable of quickly communicating the vast amounts of information between servers required to maintain adequate control and operations were generally regarded as a large barrier to widespread adoption [95][98].

Traditionally, updating grid networks and outdated industrial electricity systems with the necessary equipment was believed to be an expensive practice for the relevant stakeholders. The cost of retrofitting or installing the required smart equipment to manage local networks or allow interaction with the grid, to participate in demand side programmes and monitor performance, was historically met with reservations from the particularly change averse industrial sector [99]. In this study, interviews were conducted into the expected costs for an industrial site to prepare itself for smart grid implementation. General investment in this study was found to realistically fall between €4,000 and €6,000, however, six of the sixteen industrial sites surveyed expected the expenditure to be €10,000 or above, with one participant expecting to spend up to €36,000 [99]. This output demonstrates the perceived expense of smart grid systems within the industrial sector, which is a significant barrier to overcome. This barrier was also particularly relevant for companies with unique arrangements that were required to develop bespoke or complex systems to incorporate their specific system architectures and intricacies at higher costs [95]. The perceived high capital costs and financial requirements of implementing smart grid systems, including various equipment, operating software and external management costs, was clearly seen as a barrier to the early stage implementation of this concept. The impact of these financial costs and the reservations caused by them are further demonstrated in a survey and case study [92], although the small selection of only four relevant
industries assessed may limit the impact of its outputs. Additionally, the perception of unprofitability and lack of understanding of the potential revenue streams available through the smart grid hindered the immediate proliferation of this concept. This was particularly evident from the considerable reservations present in the case study of industries incorporating ESSs into smart grid systems [100]. Fortunately, to counteract this misconception a number of studies were conducted into the actual profitability and financial incentives available through practical applications of this concept [101]. In this study, positive profits were found in each evaluation case, with payments of over $20 per MWh reduced demonstrated in a number of scenarios. The capital cost of this concept was initially seen as a barrier, however this issue has reduced in influence as studies have provided more clarity in the area and advancements in the technology sector have led to reductions in the capital expenditures required. It is clear though, that demonstrations of the potential impact and financial performance of this concept are required to encourage further engagement from the industrial sector in the future.

Another barrier of concern identified in the literature during the inception of this concept were the dangers and impact of cyber security threats and the necessity for suitably advanced security strategies [93]. Although this aspect received less evaluation than other potential identified barriers, it is still an influential and important issue to satisfy as the implementation of this concept spreads worldwide, particularly in the risk averse industrial sector. The volume of information from meters and other smart devices on industrial sites will continue to grow, which in turn will increase the pressure and potential strain on existing cyber security systems. Continual development and advancement of security measures and privacy protection protocols will be required to ensure the safe and sustainable growth of smart grid systems [102].

In this study, a honeypot concept is designed to emulate the real traffic on an industrial communications system and monitor cyber security threats to the site before a risk to the real data occurs. This demonstrates a promising concept in this area; however, additional developments and proof of concept implementations, beyond this first industrial case study, are required to build confidence in the practice within the risk averse industrial sector. To maintain confidence, regulations and standards will need to continually be updated and developed to ensure cyber security is implemented, controlled and maintained to the highest standards [97]. Overcoming this barrier and maintaining adequate control will require cross-discipline and multi-sectoral collaboration as the risks of cyber-security threats and attacks are ever present. In the industrial setting however, this potential issue is generally satisfied by strong network and hardware encryption, firewalls and additional privacy protections that are
maintained by dedicated onsite teams and outside the specific scope of energy engineering decision makers [103]. Nevertheless, communication device requirements and the risk of cyber-security threats in this era of information is a constant concern that will need to be addressed throughout all aspects of planning, implementation and maintenance of the smart grid concept, especially in the industrial sector.

2.2.1.5 Conclusions on Systematic Mapping of the Industrial Smart Grid Concept

The industrial smart grid is an important concept within the area of energy and intelligent industrial engineering, as outlined by its global reach and impact within this sector. This section provided a definition of what the smart grid concept is, Section 2.2.1, a systematic mapping of the relevant literature in this area and a detailed overview of the specific benefits, driving factors and barriers to its adoption and widespread implementation. Through the systematic mapping process, it was illustrated that this topic, specific to the industrial sector, has matured from the initial papers published in 2010 to an area that receives steady research interest each year. The topic itself has demonstrated considerable global relevance and interest, with particular research outputs originating in China and Germany and more specifically from the North China Electric Power University and the Fraunhofer Institute for Manufacturing Engineering and Automation in these respective countries. The major benefits and driving factors of the concept highlighted in the literature, Table 3, were outlined as a valuable ability to improve grid reliability, incorporate growing levels of RESs and DERs safely into electricity grids and a marked improvement on participant’s security of supply. Furthermore, important reductions in GHGs and the ability to meet emission reduction targets on a site and national scale were demonstrated. The increased ability to gain financial incentives and maximise the performance of existing assets and resources were also found to be important driving factors of the concept. The main barriers were described as an early stage absence of clarity and understanding, a lack of suitable existing hardware and infrastructure and a believed high capital cost of implementation and lack of impact and value generation capabilities. Cyber security threats were also identified as a barrier of concern; however, as they do not fall within the scope of this research they will not be specifically addressed in this thesis. Some of the identified barriers, like the lack of suitable hardware may be mitigated through technology advancements and incentive schemes, however further research and appropriate outputs are required to adequately overcome each of these barriers, particularly the lack of clarity, perceived cost and need for better visibility of the impact and value of this concept. To ensure the sustainability and future success of this concept, it would be valuable to present further
demonstrations of successful implementations on relevant case study sites to build confidence, especially in the risk averse industrial sector. To do this, a defined and systematic framework, addressing operational risks, appropriate for the industrial sector is necessary to demonstrate the potential, including the low-risk nature, valuable financial performance and impact generation achievable through this concept.

Table 3. Table of identified benefits, driving factors and barriers of the industrial smart grid concept.

<table>
<thead>
<tr>
<th>Benefits and Driving Factors</th>
<th>Papers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Grid Reliability</td>
<td>[71][72][73][74][75]</td>
</tr>
<tr>
<td></td>
<td>[76][77][78][83]</td>
</tr>
<tr>
<td>2 Security of Supply</td>
<td>[68][77][51][79][80][83]</td>
</tr>
<tr>
<td>3 Facilitate Higher Levels of RESs &amp; DERs</td>
<td>[71][74][51][81][84][85]</td>
</tr>
<tr>
<td>4 Reducing GHG Emissions</td>
<td>[74][51][81][84][85]</td>
</tr>
<tr>
<td>5 Maximise Existing Assets &amp; Improved Energy Management</td>
<td>[78][80][82][84][85][86][87][89][90][91]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Barriers</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Lack of Clarity &amp; Defined Understanding</td>
<td>[92][93][38][94][95]</td>
</tr>
<tr>
<td>2 Lack of Suitable Hardware &amp; Infrastructure</td>
<td>[95][96][97][98]</td>
</tr>
<tr>
<td>3 Perceived Cost &amp; Lack of Impact &amp; Value Generation Visibility</td>
<td>[92][95][99][100][101]</td>
</tr>
<tr>
<td>4 Cyber Security Threats</td>
<td>[93][102][97][103]</td>
</tr>
</tbody>
</table>

2.2.2 Industrial Demand Response

A core element and enabler of the success of the smart grid is the concept of DR [63][104][105]. Industrial DR is an effective strategy to practically balance power demand and supply in real time [106]. This concept allows active participation of industrial energy users in energy grids and networks, which creates numerous benefits for the wider grid and opportunities for the site to increase energy efficiency and capture additional revenue streams [106]. Traditionally DR was defined as the process of shutting off or moving the consumption of large energy loads or energy using assets at peak grid times, under processes called load shedding and load shifting [107]. This has since developed into a more interactive and responsive process, capable of smoothing load curves, improving the reliability of national electricity grids and generating revenue for participants [63]. These traits are generally achieved through fast acting engagement, such as frequency response [108], adaptive control strategies including simulated system inertia from ESSs [78][104] and the provision of additional valuable flexibility to the overall electricity grid [60]. Crucially for the industrial sector, DR actions are defined as changes in electrical consumption from their normal consumption patterns without
jeopardizing their primary function in response to grid requirements and financial incentives at times of high electricity market variability to prevent threats to grid reliability [109]. The role and importance of DR is expected to continue growing each year, particularly as national electricity grids maintain the transition towards more RESs and away from conventional fossil fuel power stations [20][110]. An overview of DR on an industrial site is presented in Figure 8, in which examples of potential response assets and the flow of energy and information between the participating site and wider electricity grid and markets are illustrated. This demonstrates the underlying concept, where participating electrical assets or loads are signalled to respond to signals from the TSO or a DR aggregator based on financial factors or the health of the wider grid, usually indicated by its frequency shifting due to an imbalance of electrical supply and demand.

![Figure 8. Overview of industrial DR within the smart grid, outlining energy and information flows][111].

**2.2.2.1 Systematic Mapping Overview of the Industrial Demand Response Research Area**

As the concept of industrial DR was identified as a key aspect within the smart grid research area, it was valuable to investigate this topic further following the systematic mapping methodology outlined in Section 2.2.1.1. During the planning phase, the scope of this particular study was defined as research and literature specifically on the topic of industrial DR and conducted with the intention of satisfying the research questions surrounding the identification of its major benefits and driving factors in addition to any potential barriers to its successful implementation, in accordance with RQ1. The systematic mapping process was again applied to this separate specific topic, initially creating another repository and conducting the first
investigation using the search terms and databases outlined in Table 4. The initial search captured 314 papers on this research topic, with 229 papers being excluded during the first screening phase. A further 11 papers were excluded in the second detailed screening phase, resulting in 74 specifically relevant papers on this topic being identified for further review and analysis. These papers were then evaluated and analysed to determine when and where research on this topic had been published and to create a repository of papers that provide an overview of the research area and inform the research questions concerned with the benefits, driving factors and barriers associated with this concept.

<table>
<thead>
<tr>
<th>Database</th>
<th>Search Area</th>
<th>Search Terms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 IEEE Explore</td>
<td>Full Text &amp; Metadata</td>
<td>“Industrial demand response”</td>
</tr>
<tr>
<td>2 Science Direct</td>
<td>Articles with these terms</td>
<td>“Industrial demand response”</td>
</tr>
<tr>
<td>3 Scopus</td>
<td>Title-Abstract-Keywords</td>
<td>“Industrial demand response”</td>
</tr>
<tr>
<td>4 Google Scholar</td>
<td>All of the words, in the title of the article</td>
<td>Industrial demand response</td>
</tr>
</tbody>
</table>

Once the systematic mapping process was conducted, the 74 most relevant publications identified were subjected to further evaluation during the reporting phase. The publication timeline of these papers is outlined in Figure 9, illustrating that the industrial emphasis and focus in this research area began with its first publication in 2012, just two years after the initial publications in the industrial smart grid area. As the industrial DR concept was identified as a key aspect of the smart grid research area, it is not surprising that its publication timeline has followed a similar path and trajectory. Since 2012, global interest and the subsequent research output of conference and journal publications has grown and steadily increased year upon year with the exception of outputs in 2017. This exception however, correlates with the peak of industrial smart grid publications in the same year, which then begins to plateau. It is likely that the general research in the wider smart grid concept has shifted focus into more specific and innovative topics, like industrial DR, which is shown by the increase in publications and continued upward trend from 2018 onwards. The general research area, although only a decade old, has matured quickly, building on a strong foundation of industrial smart grid research and the increasing global pressure for advancements in this specific area. This can be highlighted by the share of publications, with 23 conference papers and 51 journal publications identified through the systematic mapping process. Each of these publications present reviews, case studies or potential theories to enhance or attempt to overcome the challenges associated with this concept amid the global requirement for this practice to maintain reliable control of national electricity grids with increasing levels of renewable generation.
The geographical spread of research outputs from the 74 most relevant papers identified by the systematic mapping process demonstrates a similar worldwide distribution to that of the smart grid concept, as shown in Figure 10. The industrial DR research area is most saturated in the continents of Asia, North America and Europe, with Nigeria and Australia representing the only countries contributing publications outside of these areas. Similarly, to the distribution of smart grid research the main contributors are China, the USA and Germany from their respective continents. Although in this case, Iran has the second most publications in this area with 13 papers, followed by South Korea with 7 in third place from Asia and fourth in the overall global standings. These figures are likely most influenced by the strong base of research and understanding generated by previous work in the industrial smart grid topic; however, the influence of sectoral, policy and infrastructural factors cannot be discounted. Iran for example has a particularly large number of industrial estates and developing industrial microgrid systems where case studies and numerous trials in this area are being conducted [112][113][114]. Furthermore, the impact of emission reduction targets and policies in South Korea [115] and the success of relevant DR pilot programmes [116] has driven their considerable activity in this research area.
Further to the worldwide distribution of publications in this research area, the breakdown of institutions presenting research outputs within these countries can offer pertinent findings. Of each of the countries presenting more than one publication in this area illustrated in Figure 11, China has the largest and most diverse number of institutions represented. Aside from the Shanghai and Beijing Jiaotong Universities with two publications each, every other publication comes from a different individual university. This highlights the extensive spread of research interest in this topic and the variety of different researchers and institutions involved in its development. Furthermore, the only institutions with more than three distinct publications represented in Figure 11, are the Islamic Azad University in Iran, the Colorado School of Mines in the USA and the Hanyang University in South Korea. This may indicate that the research area is still maturing, as continued dissemination of research at national and international conferences and as more journal papers are published, the research topic will continue to develop. As the research area matures, it is likely that certain institutions will increase their representation driven by individual researchers advancing their work and presenting more outputs and publications. Additionally, the diversity of research institutions represented in countries like South Korea, Germany and Spain may grow, as the success of implementations and case studies that demonstrate the considerable advantages, benefits and value of this topic, are highlighted in further detail.
2. Literature Review

2.2.2.2 Benefits & Driving Factors of the Concept

A major benefit and perhaps the most valuable driving factor of the industrial DR concept, identified during the reporting phase, is the additional control measures it provides the TSOs, assisting them to maintain the safe and reliable operation of national electricity grids [14][117]. A significant and clear international example of this benefit in practice is the ongoing success of the DS3 programme on the Irish national grid [23]. This programme of 14 grid system services, encompassing a variety of DR categories, has been pivotal in strengthening the control mechanisms available to the TSOs to maintain control of a grid with ever growing levels of RESs [89]. Through the help of these system services the programme has already assisted the increase of instantaneous RESs on the grid from 50 to 65%, with existing potential and plans in place to strive towards consistent levels of 75% and higher [23]. The ability of DR to increase the uptake and reliable control of higher levels of RESs in other national electricity grids is clear and well documented throughout the relevant literature [36]. For example, a study assessing the potential benefits of DR in Germany found that it can actually increase the utilisation of RES capacities, as the curtailment of RES plants decreases by 35 to 77% depending on the RES oversupply on the system [118]. Furthermore, the DR concept presents opportunities to the TSOs for more granular control of advancing electricity grids. The more dispersed and localised opportunities for managing the demand side of the grid presented can assist in mitigating some of the challenges of more DERs and widespread adoption of RESs across the grid network. One study demonstrates these capabilities through industrial sites.
cooperating to achieve more useful flexible capacities, however it is more focused on electricity
cost rather than grid control and so the outputs don’t maximise benefits in this area [119]. This
advantage does allow the TSOs to lessen the impact of localised transmission line congestion
and reduce any negative impacts caused by local or regional consumption or generation hubs
[35]. These valuable benefits of the DR concept to the wider grid have been and will continue
to be a considerable driving factor in the development of this topic, particularly to keep pace
with continued advancements on national electricity grids.

Another significant advantage and potentially the largest driving factor for participants and
industrial sites to engage in DR are the potential revenue streams and financial gains available.
One relevant study demonstrates the ability of industrial sites participating in real-time price-
based DR to reduce their daily energy costs by 13.31%, 9.59% and 3.72% in three different
scenarios compared to the case without DR implemented [90]. Incentive payments and
additional financial structures are used around the world to encourage additional participation
in DR schemes and ensure the capacities required are available to the TSOs. In the Irish
electricity market, incentive payments are offered for each DS3 system service to encourage
engagement and ensure participants are compensated for participation in each specific category
[25][89]. This ensures the tools are available to the TSOs to manage any scenario, from fast
demand requirements to longer term operating or replacement reserves. These incentive
payments and tariffs are common in electricity markets around the world in different guises
and to varying levels of success [110]. A study assessing the system benefits of DR through a
number of case studies on the Dutch electricity grid demonstrate this monetary benefit,
although the benefits at a site level are not analysed. In this case, DR was found to be capable
of reducing power system costs by 2.3 to 6.3 billion euro, with cost reductions attributed to
grid investment, grid losses, generator investment and generator operating costs [120]. The
influence of incentive based payments and value generation for both the participant and
provider has been particularly evaluated in practice in China, although the impact on CO\textsubscript{2}
emissions are not considered in this study [121]. The benefit of incentive structures to
encourage participation in DR and benefit each stakeholder are highlighted as well as
demonstrating this as a notable driving factor for the industrial participants. Furthermore, case
studies have been conducted in Iran to determine optimal incentive rates for incorporating large
industries into DR programmes, however the benefits to the wider grid are the focus of this
study so benefits to the individual site are not addressed or presented in detail. In this case
though, it was found that both the standard incentive rates and optimally determined rates
suggested in this paper were capable of reducing the overall total cost to the system by at least $7 million compared to the $56.6 million total cost accumulated without DR implementation [114]. This compounds the importance of incentive structures to drive the industrial engagement in DR and demonstrates the proven value generated to the wider grid network of offering these incentive payments. This topic may be key to encouraging participation from the industrial sector and would certainly benefit from further demonstrations of the impact and value available through advancements in this area.

An often-overlooked advantage of the industrial DR concept are the avoided costs and secondary benefits of participating in these schemes. The benefit of meeting international emission targets and increasing the controllable level of RESs on the national grid level is a valuable factor [89]. However, a similar positive impact can be found on an individual site level, where their DR participation can improve their financial and operational efficiency [122]. Another study addressing the challenge of reducing power consumption of industrial customers with minimal impact on production rates for DR, found that production rate metrics can be increased by up to 70% and 31% in two different case studies when a DR focused framework is applied [123]. The multi-factor advantages of DR can be clearly illustrated by the operation and quantification of benefits on a single site. Financially, a dual benefit can be seen through participation in DR, as the industrial participant receives payments through the incentive structures but also has the opportunity to reduce its demand during times of peak strain on the grid [122]. Thus, benefitting twice from the actual revenue stream and the avoided costs of reducing its electricity consumption during the most costly market times [124]. Furthermore, the value of the emissions avoided by the site, and wider national grid, through the provision of DR should not be disregarded. On a site level, the emissions offset can be particularly valuable if captured and included in site reduction targets. The emissions avoided through energy consumption reductions [125] and smart energy management in the industrial sector [105] complimented by DR participation present a significant driving factor. Capturing these emissions avoided figures and highlighting the link with DR can help to improve the green image of a company and boost corporate social responsibility initiatives. This often drives participation and emphasis in the industrial sector, as maintaining and improving a respectable image can offer a company a competitive edge [126]. This considerable benefit and value to an industrial site is further outlined in Section 2.2.4.4 of this chapter.

A further benefit of the industrial DR concept is its ability to maximise and facilitate additional positive functionalities from existing resources on both a single site and national level. For an
individual site the financial benefits are more clear, however participating in DR can also increase operational efficiency [122], assist the optimisation of DERs [51] and assist the ideal operation and performance of onsite RESs and ESSs [104]. The added benefit of increasing the operational performance is that it can reduce the payback period for often more expensive yet more energy efficient, lower emission-producing assets. Furthermore, participation in DR can benefit the cost effectiveness and profitability of ESSs on industrial sites. Offering them additional revenue opportunities through participation in DR schemes, while also offering further utilisation and dispatch options to further optimise their operation for the benefit of the site [104]. One study demonstrated that savings of up to $26,400 can be achieved for a daily operations schedule, compared to a non-responsive, no grid interaction schedule, incurring electricity costs of approximately $161,000 [87]. Unlocking the additional revenue streams for existing assets or encouraging new assets to be suitable for DR participation helps to maximise a site’s potential and increase the assistance it can offer the TSOs for balancing and maintaining reliable control of the grid. The value of DR to the wider grid can be shown in a number of ways, with one study illustrating this through an 8% decrease in full load hours and the number of load changes required per conventional power plant, which increases their efficiency and reduces their intrinsic emission output [118]. Furthermore, this study demonstrated how DR operations could further benefit the utilisation of RESs and assist the reduction of curtailment throughout the system [118], which is one of the many benefits provided by DR participation summarised in Table 5. To quantify this benefit in the Irish context, the TSOs estimated that the annual benefit of reducing RES curtailment, through the DR services captured in the DS3 programme, to be approximately €177 million in 2020 [89].
2. Literature Review

Table 5. Summary of benefits achievable through DR participation outlined in the literature.

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Figures</th>
<th>Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase the utilisation of RESs and minimise the curtailment of existing RESs.</td>
<td>A German case study found DR could increase utilisation of RESs, as curtailment decreased by between 35 and 77% based on the levels of system oversupply.</td>
<td>[118]</td>
</tr>
<tr>
<td>Cost reductions and gain financial incentives through DR participation.</td>
<td>Demonstrated ability of a site participating in real-time price-based DR to reduce daily energy costs by 13.31%, 9.59% and 3.72% in different scenarios.</td>
<td>[90]</td>
</tr>
<tr>
<td>DR enabled energy utilisation and efficiency improvements.</td>
<td>A case study site demonstrated an increase in production rate metrics of up to 70% and 31% in two different cases by implementing a DR focused framework.</td>
<td>[123]</td>
</tr>
<tr>
<td>Increased profitability and utilisation of existing infrastructure.</td>
<td>A site achieved savings of up to $26,400 on daily operations compared to a non-responsive schedule that incurred energy costs of up to $161,000.</td>
<td>[87]</td>
</tr>
<tr>
<td>Reduced energy consumption and efficiency improvements.</td>
<td>Participating in DR enabled an 8% decrease in full load hours and the number of load changes required for a conventional power plant.</td>
<td>[118]</td>
</tr>
</tbody>
</table>

2.2.2.3 Barriers to Adoption & Implementation

Through further evaluation of the relevant literature identified during the reporting phase of the systematic mapping process, one of the most frequently occurring barriers to adoption of DR in the industrial sector was found to be the perceived risk and lack of understanding of these schemes [60]. The transition towards more interactive and demand side oriented electricity markets has been met with some hesitations, similarly to the adoption of ESSs in the manufacturing industry. In this case, a study of 101 German manufacturing companies conducted in late 2016 demonstrated an average awareness, interest, expectation and perceived profitability of these systems, receiving scores of approximately 2.74 to 3.74 on a 6-point scale [127]. Organisational interest in these technologies received the lowest score, 2.74, across each of the categories. The perceived unprofitability of these systems was cited as a considerable barrier, with the lack of adequate business models and demonstrated impact and low risk of participation mentioned by the decision makers surveyed [127]. As the end-user behaviour plays a major role in the effective implementation of DR measures, the lack of immediate consumer acceptance was previously seen as a barrier to the progression and advancement of DR in the industrial sector. A key element and potential cause of this reluctance to engage was highlighted as a lack of clear understanding and standardisation of certain terminologies. A study on this topic outlines that significant differences were found when distinguishing between certain defined DR potentials, namely the technical and achievable DR potentials, which lead to aspects of the research in this area misleading potential participants [36].
Furthermore, this study states that a well-founded and user-friendly framework for analysis and quantification of DR potential would significantly increase understanding in this area and reduce the perceived risk associated with engagement [36]. To reduce the identified hesitancy and perceived risk around this topic further, the presentation of an industry suitable risk assessment framework that would appropriately reduce the level of unknowns and illustrate the potential benefits and impact of participation would help to overcome this barrier [128][129]. Continued analysis and a new systematic framework to identify low-risk industrial assets suitable for DR participation, which is not currently defined in the literature, would help to alleviate the concerns around DR participation in the industrial sector [124]. Through further investigation and analysis in this area, including additional modelling or practical demonstration of the impact and low-risk potentials available, it is feasible that this barrier to adoption and implementation can be overcome.

Another possible barrier to the adoption and implementation of this concept mentioned in the relevant literature is the willingness of industrial sites to adapt their usual behaviours and accept external influence on their energy consumption [128]. A study focusing on this particular issue, identified the lack of consumers’ acceptance as an integral barrier to the success of DR programmes and states that a suitable step-by-step methodology or framework would be crucial to overcoming this barrier [36]. Furthermore, the enthusiasm of end users to accept load interventions and DR dispatch signals is fundamental to the success of this concept. The privacy concerns and unease of industrial participants to accept signals from TSOs or aggregators was a common issue [35]. This potential challenge can be addressed with additional engagement and cooperation between the stakeholders and through the presentation of both case studies and successful demonstrations of the low risk and high reward of these DR services facilitated by a suitable methodology or modelling tool appropriate for this sector. Additionally, the varying priorities of TSOs for grid reliability and local DER owners aiming for maximised performance can create issues mentioned in the literature. However, this seldom occurs in practice as the contracts and performance agreements are designed to be mutually beneficial and capture the best of the incentives for the participant [35]. A hesitancy that is also very common in the industrial sector is the concern that DR participation will affect production or result in a reduction in output. This concern is generally based on the assumption that production assets will need to be shutoff outside of the control of the site, reducing productivity and causing industrial energy users to be wary of DR programmes [105]. This however is not the case, as demonstrated in this study, where the total energy cost of an industrial building
implementing DR can be reduced by as much as 24.12% compared to its base case without DR participation [105]. Furthermore, the concern that production assets will be impacted is also unfounded in practice, as there is considerable potential available through other non-production assets providing ancillary services on industrial sites. Through additional investigation and demonstrations of the potential of industrial AHUs or other systems, the influence of this barrier can be nullified and additional industrial DR participation encouraged [130].

A final notable barrier identified in the relevant literature is the perceived cost of required infrastructure slowing the adoption and implementation of DR in the industrial sector. The assumed cost of additional intelligent communication devices and other associated capital costs or operational expenditures required to participate in DR programmes has been shown as a common discouraging factor in its uptake [35][120]. This is largely influenced by the need for high performance frequency monitoring devices and communication equipment capable of processing large volumes of information quickly and reliably [74]. Due to the importance of near instantaneous responses and the robust validation of performance requirements, it is imperative that these devices are present on the site and located as close to the participating assets as feasibly practical [124]. These specifications and traditionally high-expected costs have influenced the uptake and consistent proliferation of this concept in the industrial sector. Although usually minimal capital expenditure is required, as industrial sites generally have the existing advanced metering and communications infrastructure already in place [48]. The monetary savings from energy reductions generally outweigh any initial costs, with additional studies demonstrating that customers can reduce overall energy consumption by 10 to 15% through DR participation [74]. The perceived cost of DR does not necessarily even materialise in practice however, as the initial capital costs are low to negligible for the majority of cases. In Ireland, the main grid aggregators and providers of this service to the industrial sector, outside of individual participants, offer the hardware and initial setup expenditures, like advanced frequency monitoring and intelligent communications devices required, to the participant at no cost [131][132]. Furthermore, a study on this topic also demonstrates that similar incentives and hardware are provided by DR aggregators in Germany [128], which further eliminates the belief that initial infrastructure costs should be seen as a barrier to DR implementation. This incentive considerably helps to encourage the continued uptake of DR in the industrial sector and minimises any potential barriers created by capital or operational cost concerns. Furthermore, the financial benefits, operational efficiency improvements and long-
term reduction in capital expenditures achievable through DR [38], help to reduce the impact of this barrier by mitigating the perceived costs even further.

2.2.2.4 Conclusions on Systematic Mapping of the Industrial Demand Response Concept

This section provides an overview and demonstration of the industrial DR research area, following the systematic mapping methodology. A summary of the research area, including its publication timeline and the intricacies of its geographical relevance were illustrated. Furthermore, a detailed depiction of the benefits and driving factors were outlined in addition to the barriers to adoption and implementation of this specific topic from the relevant literature. The annual publication trends show that this research area has received growing research interest, which has generally increased annually from its initial publication in 2012. Industrial DR has shown particular prominence in the respective continental leaders of research outputs, China, the USA and Germany. However, particular interest has also been demonstrated in Iran and South Korea, with the largest institutional contributions coming from the Islamic Azad University and the Hanyang University located in these respective countries. Through numerous demonstrated examples, the DR concept clearly offers several key benefits on both an individual site and national scale, particularly in terms of grid control and reliability, financial performance, dual cost reductions, dual emission avoidance and resource maximisation. As this is still an emerging and developing concept there are potential barriers surrounding the perceived risk, behavioural changes and believed cost of implementation and participation in this concept. The identified benefits and driving factors in addition to the possible barriers identified in the relevant literature are outlined in Table 6.

Table 6. Table of identified benefits, driving factors and barriers of the industrial DR concept.

<table>
<thead>
<tr>
<th>Benefits and Driving Factors</th>
<th>Papers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Assisting Grid Control &amp; Reliability</td>
<td>[89][14][117][23]</td>
</tr>
<tr>
<td>2 Revenue Streams &amp; Financial Gains</td>
<td>[36][118][119][35]</td>
</tr>
<tr>
<td>3 Dual Cost &amp; Emission Avoidance &amp; Reduction</td>
<td>[89][90][110][114]</td>
</tr>
<tr>
<td>4 Maximisation of Existing &amp; Provision of Additional Resources</td>
<td>[120][121]</td>
</tr>
<tr>
<td></td>
<td>[89][105][122][123]</td>
</tr>
<tr>
<td></td>
<td>[124][125][126]</td>
</tr>
<tr>
<td></td>
<td>[51][87][89][104]</td>
</tr>
<tr>
<td></td>
<td>[118][122]</td>
</tr>
<tr>
<td>Barriers</td>
<td></td>
</tr>
<tr>
<td>1 Perceived Risk &amp; Lack of Understanding</td>
<td>[60][36][124][127]</td>
</tr>
<tr>
<td>2 Behavioural Changes &amp; Acceptance of External Influences</td>
<td>[105][36][35][128]</td>
</tr>
<tr>
<td>3 Perceived Cost</td>
<td>[130]</td>
</tr>
<tr>
<td></td>
<td>[74][38][35][120]</td>
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<tr>
<td></td>
<td>[124][128][48]</td>
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</tbody>
</table>
These barriers identified in the literature can be mitigated and some studies have alluded to potential strategies; however, they need to be addressed further through additional appropriate demonstrations of actual implementation on industrial sites to illustrate the impact and financial performance achievable to overcome these barriers suitably. Overall, industrial DR shows considerable benefit to an individual industrial site and the wider electrical grid, with significantly more potential achievable through developing certain knowledge gaps and further demonstrating the value of this concept. One particular area that may offer additional value is the investigation of non-critical assets, like AHUs serving non-critical areas, on industrial sites participating in DR programmes. Demonstration and analysis in this area would help to nullify many of the identified barriers to this concept and would further highlight the valuable potential and help to encourage additional DR participation in the industrial sector. Finally, to reduce the hesitancy and perceived risk identified as a barrier to this topic effectively, a systematic risk assessment framework suitable for the industrial sector is required to build confidence, minimise the level of unknowns and ensure sceptical participants are guided through the process. Throughout the systematic mapping process and further evaluation of the relevant papers, a number of important concepts and terminologies within these research areas were identified. The following section of this thesis will outline, expand upon and discuss some of these most relevant concepts to ensure a suitable review of the research area is presented.

2.2.3 Integral and Influential Concepts

During the review of relevant literature in Sections 2.2.1 and 2.2.2, a number of concepts were identified as integral and influential to the smart grid and DR research areas. Specific concepts like flexible capacity, industrial DSM and “prosumers” were frequently cited in the literature and mentioned as integral aspects to this research area and additional measures to assist the overcoming of its barriers. As a result, they have been further evaluated and discussed in the following sections to present a suitable definition and highlight their relevance to the topic. Dual benefit analysis, identified as a benefit of industrial DR is also outlined, demonstrating how this concept has been achieved in practice. Furthermore, the influence and potential transferrable knowledge of residential and commercial concepts in this research area are explored to evaluate their impact on the industrial sector. Finally, the VPP concept is defined, including important terminologies, demonstrating its value and potential influence on the research area as a current enabling factor and important aspect in the future of smart grids and DR implementations. Overall, the intention of this section is to outline and critically evaluate
the influential subsidiary concepts identified in this research area, to provide a deeper understanding of the topic based on the relevant literature.

2.2.3.1 Flexible Capacity

An important concept and frequently used terminology in the energy and smart grid area is flexible capacity. In the constantly evolving electricity grids, with higher levels of variable RESs, additional sources of flexibility are required to ensure the TSO can maintain reliable control of the grid. Grid flexibility smooths the process of balancing electrical supply and demand and helps maintain overall reliability [129]. Grid flexibility can be provided from several aspects on the demand side, including DR, but also on the supply side and through the provision of intelligent storage solutions. Flexible capacity on the demand side comprises of suitable capacities on the demand side that can adapt their consumption over a specific duration to balance variations in the electrical grid [129]. This flexible capacity can also be defined as capacity that can shift the time that energy is drawn from or exported to the grid by behind-the-meter resources in response to an external signal [133]. The concept of flexible capacity aligns very closely with DR, providing similar benefits, like grid reliability and the facilitation of RESs, while also contributing as a driving factor in the continued uptake of the concept.

Increasing the levels of flexible capacity within electricity grids, if managed properly, can provide a range of services, including frequency regulation and congestion management to the TSOs. These services can greatly assist their ability to manage and counteract the variability and uncertainty introduced by high levels of DERs and RESs [33]. Studies have been conducted into how the maximisation of flexible capacities can affect the ability of users to provide services to the grid in addition to balancing their own consumption to reduce any strain before it influences the grid itself. An example of this can be seen in the context of electric vehicles, where the energy stored in the fleet can provide flexibility when the fleet level charging schemes are suitably optimised. In this particular study, each of the eight electric vehicle charging points were capable of offering up to 6 kW of instantaneous flexible capacity while the delivery durations were based on the vehicle state of charge and energy requirements at the time the flexible capacity is required [83]. Flexibility can also be achieved on individual sites or industrial micro-grids through the implementation of targeted load management strategies. One paper presents such a study, where strategies aim to leverage the thermal inertia of a large two-storey building using both thermal energy storage and the heating system [134]. In this case, the thermal ESS, consisting of three heat pumps, was capable of successfully offering up to 120 kWh of flexible capacity across a working week or temporary reductions of
approximately 20 kW for shorter load shedding applications, compounding the potential available for participation in DR programmes. Another study evaluates the challenges of optimising a micro-grid system incorporating ESSs, wind and solar generation to maximise the efficiency and flexible capacities available from a 100% renewable energy microgrid system [32]. This study demonstrates the value of flexibility on electricity grids to maximise existing assets and provide additional resources, like a key benefit of DR, however this paper only focuses on the cost reductions and financial implications of this concept and none of the wider benefits beyond this factor. Nevertheless, through the utilisation of flexible capacity operations, this study demonstrates a project investment reduction of approximately 12.5%, attributed largely to a 7% cost reduction proportion of the ESS to total investment due to a smaller system being required to achieve equal or better output [32].

The influence of flexibility on current electricity grids and the potential changes required to adapt and achieve the maximum benefit of this concept are vital to maximise the ability of TSOs to maintain reliable control of adapting electricity networks. As the importance of providing flexible capacity to the grid grows, the markets and incentive structures will need to be re-evaluated to match their value. One paper presents a new electricity market structure to adequately represent and capture the value of flexible capacities and their influence on grids with higher levels of renewable penetration [135]. Although this study does not address the benefits achievable in a specific sector or on an individual site level, it does demonstrate an overall capacity and energy market cost reduction of 0.81%, meaning the TSO can maintain equivalent or better control of the system at a lower cost. Furthermore, through the additional measures provided by the flexible capacities, the curtailment of load (5.3 MWh), wind (7.3%) and solar (13.1%) power could also be reduced, leading to a more flexible generation mix and a system that can accommodate higher system loads and RES levels [135]. The flexibility of certain industrial processes has received some investigation to increase and develop the potential responsiveness available in this sector. An example of this is shown through the investigation of the ability of the chlor-alkali process for the production of ethylene-dichloride to provide flexible capacity in day-ahead and reserve markets [110]. Although this is a specific industrial process and generally requires excess capacities in the process and storability of final or intermediate goods to achieve the maximum benefit, relative wholesale electricity savings of 86.57%, 87.46%, and 81.16% in 2008, 2015, and 2030, respectively were demonstrated in this study [110]. While this example outlines useful flexible capacity potential in the industrial sector, it also further demonstrates the need for a more general and accessible approach to
identify similar flexibility in the wider industrial sector. Based on this conclusion and the previously outlined need for additional flexibility in the national electricity grid, a systematic framework to identify low-risk assets common throughout the industrial sector to provide this flexible capacity is needed to increase engagement and encourage new participation from the industrial sector.

2.2.3.2 Industrial Demand Side Management

Industrial DSM is active in the same area and in a similar manner to DR, as a sophisticated concept and method for energy users to change their energy consumption patterns [74]. It is a key enabler for energy users to control, monitor and adjust their electricity consumption patterns in real time, largely driven by the same factors as DR programmes. This similarity has frequently led the terminologies to be used interchangeably throughout the relevant literature. However, DSM differs slightly from DR in that it is a wider scope strategy, focused not only on responding to grid requirements and market signals but also more general aspects including energy optimisation and cost reductions internal to the site [87]. DSM can be defined as the planning, implementation and monitoring of those utility activities designed to influence the customer’s use of electricity in ways that will produce desired changes in the utility’s load shape, pattern and magnitude [136]. These management measures on the demand side to influence its load shape and characteristics can broadly be divided into two categories, energy efficiency measures and DR strategies [36]. In general terms, these two categories can be considered as permanent and flexible temporary load reductions respectively.

A clear example of the multi-factor benefits of DSM can be demonstrated by a scheme studied on a refinery plant in the industrial sector [137]. In this case, the energy efficiency and cost optimisation measures were applied, resulting in the adjustment of certain energy intensive activities from peak to off peak hours, however, the study did not investigate the frequency response potential of these flexible assets. The studied adjustment did help to reduce the site’s energy and operational costs by up to 6.5%, while also providing the platform for additional energy market participation based on the systems and operational information gained [137]. A similar implementation was carried out in another industrial setting, where a modelling approach was used to determine its load shifting capabilities. A smart operating schedule was proposed to shift non-priority loads to more optimal times, while ensuring all priority loads were on at all times and the power balance constraint was always satisfied [87]. This study demonstrates the successful implementation of this load shifting operation; however, there is very little detail of the asset prioritisation and categorisation process and no mention of
industry-recognised criticality or risk rating standards or processes, which are important in the risk averse industrial sector. DSM can also be applied in the management of heating and domestic hot water in flexible buildings. An example of this is demonstrated by a smart low-carbon heating system incorporating a DSM controller to decide the most favourable procedure of energy management. This controller provides the required hot water using a thermal energy storage unit as a support system to enable it to operate at the most optimal times [138]. Through this DSM operation, the system was able to achieve economic savings of 4% and 20% for end-users and 12% and 25% for retailers respectively, while also reducing overall CO₂ emissions by moving the electricity consumption to times with lower grid CO₂ emission rates [138]. The success of these schemes and their illustrated benefits demonstrate the value of additional analysis and discussion in these areas, highlighting the need for further evaluations to identify achievable capacities and demonstrate their impact potential to encourage new and continued engagement from the industrial sector.

2.2.3.3 “Prosumers”

Another important concept and prevalent terminology in this research area is the practical application of energy users as “prosumers”. A prosumer is defined as both a producer and consumer of energy [139] and is represented to the grid as a two-way flow of energy, Figure 12, or both a load and generation resource [140]. A prosumer can operate in producer or consumer mode and in some cases even combine these modes to supply energy to the grid while simultaneously consuming it [74]. Prosumers can re-sell or re-supply their surplus energy produced by onsite RESs to utility providers or operate in self-consumption mode, thus optimising their energy efficiency [74]. The prioritisation of self-consumption ensures a prosumer maximises its own generation resources and minimises its costs and reliance on its grid connection, highlighted as one of the main driving factors of the smart grid concept. The largest benefit of this concept comes at times where its generation resources are more valuable to the grid. The prosumer can then become an energy supplier or offer discrete intervals of self-consumption to benefit the TSO and wider grid network [141].
2. Literature Review

This concept has been particularly important in encouraging industrial participation in electricity markets and driving engagement in DR schemes [128]. One particular study assesses and analyses the optimal operation of an agro-industrial site operating as a prosumer to maximise its exploitation of onsite RESs [139]. In this study, a monitoring and management system was outlined that presented a number of operational and energy management benefits, including seven flexible loads, ranging from 10 kW to 144 kW, available on the site to participate in grid response schemes [139]. This study also provided the platform for further engagement with the grid to manage consumption on the demand side effectively. Another study applies a game theory based load management tool to optimise the performance of prosumers in an industrial micro grid. This application allows the prosumers to manage their loads to maximise generation sources and smooth their consumption profile, notably reducing peak consumption by up to 15%, thus optimising the studied distribution networks overall energy performance [141]. The prosumer concept has demonstrated clear value to the area of interactive and responsive electricity grid participation, with valuable advantages in cooperation with RESs, DERs and ESSs on industrial sites [81][59]. This concept is closely aligned with the practical application and benefits of both the smart grid and DR concepts, proving to be an additional driving factor of their success from the relevant literature.

2.2.3.4 Dual Benefit Analysis

A number of direct and indirect benefits of industrial DR were highlighted in the previous sections, with financial performance and emissions reductions featuring prominently. In both
of these cases, responding to a DR event offers the dual benefit of both reducing consumption while simultaneously avoiding additional costs and emissions, therefore providing a two-fold benefit to the participant or wider grid. In the literature, the financial benefit is most commonly discussed as a tangible and quantitative driving factor for this concept. In one such paper, the additional cost savings of cooperative industrial DR is presented [119]. This study presents an optimisation-based framework to assess industrial loads shifting their operating schedules to achieve cost savings. This study highlights the dual benefits provided by this concept through demonstration of the avoided costs and savings simultaneously achieved by responding to these DR events. It does not extend beyond the peak shifting capabilities of DR however, only focusing on the cost savings of adjusting operations from peak price periods to times with lower electricity costs [119]. This study illustrates some of the financial benefits achievable through DR but does not fully capture the additional aspects including incentive payments or the benefit to the wider grid. Another study, presenting a price based DR algorithm for industrial facilities participating in DR also highlights the dual benefits of participating in these programmes [90]. This study demonstrates the ability to minimise electricity costs for an industrial facility with DR but only focuses on real-time pricing and the financial aspects associated with grid electricity costs not incentive payments or additional financial benefits for the individual site. Furthermore, this study does not incorporate any coordination with the TSOs or consider the impact or benefits for the wider electricity grid. The dual benefit captured through reduced electricity costs and peak demand reductions are presented as the main benefits, which are importantly captured without affecting the operational constraints of the industrial facility in focus [90].

The dual benefits associated with participating in incentive-based DR programmes are outlined in one study that further describes the electricity customer’s psychological factors that also influence its performance [142]. This study focuses on the financial benefits achievable through incentive schemes while also investigating the TSOs carbon emissions abatement and incentive strategies, however, it only presents a general outlook not specifically focused in the industrial sector. The customer or participant psychological factors investigated include carbon awareness and capture the reductions achievable but do not include other influential factors like the perceived risk of participation or challenges of getting further participants to engage in DR. Although the predominant focus is on the influence of carbon taxes, describing how these can affect financial performance, the emission reduction capabilities of DR are also demonstrated in this study. The carbon emission benefits are captured through the avoided
emissions achieved through DR instead of balancing the energy requirements with higher emission producing peaking plants [142]. This allows a number of scenarios representing the reductions achievable through DR to be presented in this study, however, the emissions and intrinsic costs are based on generating electricity from individual fuel sources, not the wider grid and its actual generation mix supplying the consumer in question. Another study, presenting an evaluation of DR activities in the industrial sector also highlights the dual benefits and carbon emission reduction capabilities of DR [117]. This study evaluates the carbon reductions and avoided emissions using the actual grid emission factor and the overall emissions balance, as described in Equation (1) and (2). This study incorporates certain production equipment and other industrial asset capacities into its hypothetical flexible capacity and so the avoided emissions, CE$_1$, are counteracted by the additional carbon emissions created by the additional electrical consumption before, CE$_2$, and after, CE$_3$, the grid event in its evaluations. This would not be the case for interruptible assets or support systems, like AHUs, that could be shut off in response without overconsumption before or after the event. Following further evaluation or operational risk analysis this could be demonstrated in practice, to show no additional consumption would occur as long as operational constraints were not exceeded during the event duration.

\[
CE_{Total} = CE_1 - (CE_2 + CE_3)
\]  

\[
= \sum_{k=1}^{n} E_1^k \cdot f_k - \left[ \sum_{k=1}^{n} E_2^k \cdot f_k + \sum_{k=1}^{n} E_3^k \cdot f_k \right]
\]  

The total carbon emissions, CE$_{Total}$, in this study are calculated as the final sum of the durations, E$_1$, E$_2$, E$_3$, and actual emissions factors, f$_k$, to demonstrate the actual emissions avoided throughout the lifecycle of the DR event. In addition to the carbon emission benefits, this study also outlines the financial benefits achievable through industrial DR however, it is focused only on reserve energy markets, not frequency or any other response categories and does not factor incentive or TSO performance payments into its evaluations [117]. Finally, while this study does present the clear identification of flexible capacities, this is done through aggregated averages of typical load profiles and so analysis is not based on actual asset capacities. These average daily load values offer a representative figure for evaluation, but they do not incorporate or evaluate any associated risk or asset specific considerations into the analysis. The dual benefits, for both financial performance and carbon emission reductions discussed,
further demonstrate the value of implementing this concept, offering a clear opportunity to analyze and evaluate its impact within the industrial sector.

2.2.3.5 Experience from the Residential Sector

The residential sector has also been influenced by the general factors, like emission reduction and energy efficiency targets driving the uptake of smart grid and DR strategies present in the industrial sector. Having also benefitted from the proliferation of smart devices and advancements in communication technologies in recent years, valuable experience and transferable knowledge can be gained from this sector. An interesting investigation of the impact of Non-Intrusive Load Monitoring (NILM) in the residential sector provides a good example of the value generated from collecting additional energy data [143]. This collected energy data allowed the comparison of present compared to previous consumption data, which assisted the users to identify energy efficiency and reduction measures in this study. Furthermore this low cost, only $11 proof of concept system is also capable of providing a more detailed view of the users energy consumption patterns, which can provide additional benefits to the user and TSO [143]. The NILM concept can help to reduce the hardware and maintenance costs of energy monitoring and avoid complex installations that may intrude on the electrical network. In another study, a NILM system combined with a neural network algorithm demonstrated that it was capable of discerning three different loads, a 900 W vacuum cleaner, a 600 W hair dryer and a 1200 W vacuum cleaner, individually through a number of different combinations at 100% accuracy [144]. These advantages and capabilities demonstrated on the residential scale make this concept desirable for implementation in the industrial sector. The transferrable learnings could benefit energy management projects and facilitate improvements on the demand side, which may encourage further engagement from the industrial sector in flexible capacity and response programmes.

Another relevant concept in the residential sector is the formation of CCA programs. These are entities formed by cities or counties to serve the energy requirements of their local residents and businesses, incorporating a large group of small energy users into a single aggregation [145]. These programs typically give local governments more control over their energy mix and provide opportunities for better rates by entering larger quantities into the wholesale market. CCAs have demonstrated the ability to increase the utilization of locally sourced energy and use of RESs through incentive schemes and even power purchase agreements, similarly to the industrial sector [40]. Furthermore, CCAs with notable levels of residential scale generation like rooftop solar and ESSs like batteries, can offer this renewable energy and flexible capacity
2. Literature Review

The aggregation structures and potential for further collaboration and larger resource aggregations offer valuable potential to the industrial sector to create their own similar aggregation of energy using assets or collaborate with residential users for mutually beneficial projects. In one study, a coordinated aggregation of industrial and residential energy users were demonstrated to be capable of saving up to 14% on operating costs by participating in a DR programme together [146]. Approximately 1% carbon emission cost savings were also achievable through this coordinated approach compared to an individual participation approach demonstrate in this study.

Valuable knowledge can also be gained from the experiences of Home Energy Management Systems (HEMS) in the residential sector and their ability to enhance performance and participation on the demand side. HEMS are defined as the optimal system to provide energy management services to efficiently manage and monitor electricity consumption, generation and storage in smart houses [147]. These systems allow controllable household appliances, including thermostatically controlled, non-thermostatically controlled and ESSs in residential settings, to play a role in DSM structures. The most common thermostatically controlled appliances in the literature are electric water heaters, heat pumps and residential HVAC systems, however non-thermostatically controlled appliances, like washing machines and tumble dryers were also investigated [147]. Additional studies in the residential sector present further potential value from incorporating HVAC systems into DR programmes as well as the significant opportunities to aggregate their available capacities with other suitable sectors [148]. This study however, only investigates the impact of set point changes on the DR potential and does not evaluate shutting off the assets for short periods suitable for frequency response programmes to benefit the electricity grid. The potential of these assets discussed in the residential sector and confidence gained through their successful incorporation into DR programs offers encouragement to similar applications in the industrial sector, particularly for assets like HVAC systems that on an industrial scale would have larger capacities to respond. This highlights the research gap surrounding industrial assets, like HVAC systems, that have yet to be fully evaluated for DR and illustrates the potential value of further analysis and discussion of the potential impact and value these assets participating in DR may provide to national electricity grids.

2.2.3.6 Experience from the Commercial Sector

The commercial sector also offers potentially valuable experience and transferable knowledge to industrial participation in DSM practices, particularly as it also encompasses large individual
assets and potentially similar scales of energy consuming portfolios. The smart grid interaction capabilities and DR response potential of the commercial sector has received some attention in the relevant literature. Studies to evaluate and uncover its potential to reduce or shift its electricity consumption patterns to improve grid control and reliability have received the most extensive evaluations [36]. One particular investigation highlights the potential for commercial chiller systems to participate in fast DR events. This study presents a model predictive control strategy to optimise the chiller power demand and cooling discharge of storage to allow for maximum and stable power reduction in response to a grid event. This demonstrated that flexible capacity could be delivered from commercial chillers reliably, without jeopardising onsite requirements to satisfy the needs of a grid DR request [41]. In this case, almost 1200 kW, approximately 40% of the chiller power demand compared to the baseline for this study, could safely be reduced for DR without affecting operations. A similar control strategy was also implemented in the commercial sector to evaluate the performance of building heating systems to participate in DR programmes. This study evaluated the potential of numerous scenarios in the commercial sector, from a three-zone commercial office space to a five-floor commercial building composed of 20 different heating zones [42]. The output of this study compounds the applicability and suitability of these systems for DR; however, its scope is bound largely to price-based demands and electricity bill reduction rather than overall DR performance. A further study of the price-based DR potential of commercial buildings with multi-zone office spaces provides additional confidence to their response capabilities. The results of the proposed approach demonstrate that it is possible to incorporate HVAC systems in commercial office spaces into DR programmes without incurring unacceptable impacts on the thermal conditions within the zones [149]. In this study, peak load curtailments of 7.19% to 21.7% and 14.34% to 26.84% for high to low comfort occupants at 1°C and 0.25°C set point intervals respectively are safely achievable. This technique further highlights the peak demand reductions available from these assets and the considerable potential benefits that could be afforded to the wider grid through further implementations of this concept.

Another study presents a detailed investigation of the potential for a case study commercial building to offer some of its electrical loads for DR and even operate as part of a wider response aggregation. This study considers a number of deferrable loads, again including heat pumps, AHUs, and circulating pumps to illustrate the commercial buildings DR capabilities [44]. This study further highlighted the potential of HVAC systems to provide flexible capacity to the grid without risking the thermal environments they serve, which could be equally as relevant.
and applicable in the industrial sector. For this case study building, it demonstrated an ability to shed its load by an average of 109 kW, corresponding to 46.4% of the building total load. Furthermore, this study demonstrated that if the building were deployed as a VPP for four-hour responses, it could offer an initial power of 28 kW and stored energy of 401 ± 117 kWh 100% of the time, 109 kW and 571 ± 82 kWh 41.5% of the time and 138 kW and 625 ± 18 kWh 24.6% of the time [44]. Additional studies have also investigated the potential energy flexibility within commercial buildings, in one particular case, considering the building thermal mass, electrical equipment, HVAC systems and occupants’ behaviour. This study identified clear useful flexible capacity in the single-function commercial office building that could be captured through the energy management system to respond to GFEs [150]. In this study, values of 37.7%, 46.3% and 53.6% of total building electricity flexibility can be achieved through the HVAC system with a storage tank across three scenarios, from base case, an additional 1°C and 2°C temperature increase from the norm. Further studies in this area investigate the thermal inertia of the thermal mass of commercial buildings as well as coupling the thermal inertia of their air conditioning systems to maximise DR potential [151]. Through the experimental modelling platform of this study, it is possible to highlight the DR potential of chillers and air conditioning units, which can safely provide useful capacities in the commercial sector. In this case, a reduction of peak electricity consumption of 16.74% can be achieved through the air conditioning system, while an additional 1.93% reduction can be achieved by also incorporating the chilled water system. The valuable experience and knowledge gained from these examples and case studies in the commercial sector present interesting concepts and strategies that may be transferable to implementation in the industrial sector. This potential transfer of knowledge, particularly of the DR potential of HVAC and chiller systems offers an interesting and potentially valuable resource to be uncovered in the industrial sector. Cross-sectoral demonstrations and knowledge sharing is not uncommon and in the area of energy management and DR offer promising collaboration and continued improvement opportunities [88].

2.2.3.7 Virtual Power Plants

The VPP concept offers industrial facilities and other large energy users previously unable to engage, the opportunity to participate in electricity market programmes [152]. VPPs are a mechanism for controlling and managing an interconnected aggregation of assets, including but not limited to, DERs, ESSs and flexible loads, as shown in Figure 13, enabling them to participate in the market in the same manner as a conventional power plant [46][153]. A VPP
commands a total capacity similar to that of a conventional power plant but appears to the market and TSOs as a variable-size power plant [98]. The inherent flexibility and responsivenes provided by a VPP has led to considerable advancements in this area from its inception to current best practices. Initially this concept was only used to manage large groups of micro-generators whose total capacity was comparable to that of a conventional power plant [140]. Whereas in today’s electricity markets, VPP’s can be seen as instrumental in seamlessly incorporating growing levels of RES while aiding the continual balancing of the overall network, attributes that are also fundamental to the DR concept. Additionally, the VPP concept further enables and promotes the ability of large energy users to participate in DR, operate as prosumers and actively engage in the national electricity markets [140].

![Figure 13. Overview of a VPP, including bi-directional flow of power with the electricity market and examples of contained assets [45].](image)

VPPs as a concept, are still developing and at a relatively early stage, but the overriding philosophies can generally be categorised as one of either a Technical VPP (TVPP) or Commercial VPP (CVPP) strategy [59][113], outlined in Table 7. The main function of a TVPP is to provide response, system balancing and ancillary services to the local network. Operators of TVPPs require detailed information on the local network and generally work for or very closely with the TSO. As one of their key functions is to support the local network, TVPPs typically consist of DERs and incorporated assets within a relatively local geographic location [154]. CVPPs prioritise trading within the wholesale electricity markets, ranking maximized financial performance over their impact on the distribution network. The operator of a CVPP can be any third-party aggregator with market access, as direct collaboration with the TSO is
less critical to targeted performance. CVPPs are not constrained by geographical location as
the local network has little effect on their overarching goal. Therefore, CVPP aggregation
portfolios can be particularly dispersed over very large areas [154].

Table 7. Overview of technical and commercial virtual power plants, outlining the main influences and
differences between the two philosophies.

<table>
<thead>
<tr>
<th>Definition</th>
<th>TVPP</th>
<th>CVPP</th>
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<tr>
<td>Key Goal</td>
<td>Technical Virtual Power Plant</td>
<td>Commercial Virtual Power Plant</td>
</tr>
<tr>
<td></td>
<td>Benefit Local Grid Network</td>
<td>Financial Performance</td>
</tr>
<tr>
<td></td>
<td>Provide Response</td>
<td>Optimize trading within the wholesale markets</td>
</tr>
<tr>
<td>Main</td>
<td>System Balancing</td>
<td></td>
</tr>
<tr>
<td>Functions/Services</td>
<td>Grid Ancillary Services</td>
<td></td>
</tr>
<tr>
<td>Location Influence</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>TSO Influence</td>
<td>High</td>
<td>Low</td>
</tr>
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The VPP concept has demonstrated potential in the residential sector [39], in this case through
the implementation of VPP infrastructure in a flexible house setting, highlighting that
approximately 17% of the heat load can be safely shifted as a flexible load. The VPP concept
also offers flexibility and cost savings measures on larger scales to optimise aggregated load
and generation units [155], as well as in thermal and electrical systems, particularly
incorporating and maximising the operation of CHP units [156]. The value of this concept can
also be demonstrated in the industrial sector, with one study investigating the load shedding
capabilities of an industrial TVPP under load change and single line outage contingency
scenarios [113]. In this case, the combined load shedding capability of two investigated TVPPs
was 6348.82 MW, a 25.96% improvement on operations without the proposed load change
framework. The improvement of these same two examples was 32.92% under the single line
outage scenario, equating to a total load shedding capability of 4530.49 MW [113]. A similar
VPP framework also demonstrates its cost saving performance capabilities in this sector
through implementation of a correlated DR programme. In this study, cost savings of
approximately 28% are achievable through the implementation of DR programmes facilitated
by the VPP structures [157]. The underlying practice of aggregating supplies, loads and energy
stores has the potential to re-shape the landscape of the utility market by enabling increasing
levels of prosumers to benefit the grid. The VPP concept also provides a structure and cost-
effective path to drive new participants to engage in response programmes, which may be
instrumental in encouraging additional uptake within the industrial sector to capture previously
unachievable flexible capacities.
2.2.3.8 Conclusions

Through the additional concepts, transferrable knowledge and driving factors outlined in this section, which compliment, influence and further develop on the smart grid and DR concepts outlined in Sections 2.2.1 and 2.2.2 a number of conclusions can be drawn. These important aspects have demonstrated their influence on the research area, especially supporting and helping to overcome some of the key barriers to smart grids and DR programmes, including the perceived cost, lack of understanding and potential risk of implementations. This factor and mitigation of some of the barriers can help to encourage further uptake of these concepts, however, it is clear that additional implementations and successful demonstrations of the concepts in the industrial sector are needed to capture the value in this area fully. Additionally, the flexible capacities potentially achievable from HVAC systems, chillers and specific building types identified in the previous sections and outlined in Table 8, require further practical investigation and modelling analysis to uncover similar potentials and value within the industrial sector.

Table 8. Summary of relevant benefits achievable.

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Figures</th>
<th>Paper</th>
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<tbody>
<tr>
<td>Flexible capacity from commercial building thermal energy storage and heating system.</td>
<td>Potentially 120 kWh of flexible capacity across working week or approximately 20 kW for shorter load shedding applications.</td>
<td>[134]</td>
</tr>
<tr>
<td>Demonstrated flexible capacity available from commercial chillers.</td>
<td>1200 kW or approximately 40% of chiller power demand compared to study baseline.</td>
<td>[41]</td>
</tr>
<tr>
<td>Commercial office space HVAC systems participating in DR programmes.</td>
<td>Achieved peak load curtailments of 7.19% to 21.7% and 14.34% to 26.84% for high to low comfort occupants at 1°C and 0.25°C set point intervals.</td>
<td>[149]</td>
</tr>
<tr>
<td>Demonstrated ability for a commercial building to shed load safely.</td>
<td>Achieving an average of 109 kW, corresponding to 46.4% of the building total load.</td>
<td>[44]</td>
</tr>
<tr>
<td>Flexible capacities achievable from residential heating systems.</td>
<td>Approximately 17% of the heat load can be safely shifted as a flexible load.</td>
<td>[39]</td>
</tr>
<tr>
<td>Flexible capacity in single-function commercial office building captured through the energy management system.</td>
<td>37.7%, 46.3% and 53.6% of total building electricity flexibility can be achieved through the HVAC system with a storage tank, from base case, an additional 1°C and 2°C temperature increase.</td>
<td>[150]</td>
</tr>
<tr>
<td>Demonstrated DR potential of commercial chillers and air conditioning units.</td>
<td>A 16.74% reduction of peak electricity consumption can be achieved through the air conditioning system, with an additional 1.93% reduction achieved by also incorporating the chilled water system.</td>
<td>[151]</td>
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</tbody>
</table>
The evaluations will need to consider aspects including any risk of participation in DR schemes, impact on internal air temperatures and suitability for different response categories, as highlighted by the experience gained from existing examples. Furthermore, these studies outline that additional demonstrations of the actual impact and benefit achievable by increased flexible capacity contributions from the industrial sector are required to encourage greater participation from this sector effectively. To achieve this goal, it is clear that a systematic framework to identify potential flexible capacities and a modelling tool to evaluate the low-risk opportunities, suitable for this sector, are required to ensure the previously identified barriers are effectively addressed and eliminate their impact. To develop this appropriate framework and avoid the barriers of perceived risk and lack of understanding successfully, it is important to appraise existing examples and related works or relevant defined best practices and industry recognised standards to develop a new framework appropriate for this sector. The following section presents an overview of some of these relevant methodologies, techniques and modelling approaches to clearly outline this area and ensure the key barriers mentioned are suitably addressed by the proposed novel framework.

2.3 Review of Influential Methodologies and Approaches

As highlighted in the relevant literature detailed in Section 2.2, further evaluation and demonstrations of the low-risk DR performance potential in the industrial sector are required to overcome the barriers to its continued adoption and clearly illustrate the potential impact it may provide on a national scale. This is crucial to ensure its full potential is achieved and DR capabilities outside of dispatchable generators can contribute to the expected 806 MW to 1206 MW of DR capacity required from this sector by 2030 [158]. The additional value of incorporating low-risk assets to supplement existing capabilities is that new technologies like generators, which may be more carbon intensive, or storage, which may be expensive, are not required as existing assets are utilised. A key aspect to mitigate the impact of identified barriers surrounding a lack of understanding, perceived risk and the acceptance of external influences is to base any proposed framework or novel tools on industry proven standards and recognised techniques. As this is essential to new evaluations in this area and the continued advancement of this concept, it was important to evaluate previous methodologies and techniques to build any future works on a strong foundation and ensure confidence in the procedures for implementation in the risk averse industrial sector. The following sections present this evaluation of influential methodologies and techniques to develop an appropriate framework.
for application in this sector. Furthermore, specific modelling approaches and guidelines relevant to applications in this area are explored, as a useful process to evaluate and demonstrate potential risks virtually, before final decisions are made in practice as part of an overall decision-support and risk assessment framework. The underlying intention is to form the basis for a prescriptive framework to advance industrial participation in DR schemes and provide decision support to inform and encourage additional participation from this sector. The development of an appropriate risk-assessment modelling tool, as part of this framework, to evaluate and demonstrate any operational risk of suitable assets selected for participation is also important to minimise any perceived risk, which can help to overcome a key barrier of this concept.

Following a hierarchy shown in Figure 14, similar to that presented by the GreenSAM project, a framework will be understood as the overarching term for an overall process or procedure containing a number of steps intended to achieve a specific principle goal [159]. This definition is based on a number of other studies presenting systematic frameworks for a clear purpose [160][161][162], which contain different influential methodologies, tools and techniques as part of the fundamental process steps that together help to achieve the overall framework goal. A methodology can be viewed as an umbrella term to describe a process, a number of iterative steps or a defined understanding to provide a specific output within an overall framework [159]. A tool is classified as a process that presents a defined result or set of outputs that can be utilised independently or as part of a methodology, which influence the next steps and benefit an overall framework, helping to strengthen and successfully achieve the overall common goal. Finally, a technique is viewed as a defined activity or simple exercise that is utilised during the development or implementation of any of the process steps as part of a tool, methodology or overarching framework.
2.3.1 Influential Methodologies and Techniques

From the review of relevant literature, it was found that a prescriptive framework suitable for the industrial sector is required to overcome the believed risks and encourage additional engagement in DR from the industrial sector effectively. To ensure a proposed novel framework is in fact suitable and based on appropriate methodologies and recognised techniques it was important to evaluate previous examples and relevant studies. The goal of doing this is to ensure that the previously identified barriers, particularly lack of clarity, understanding and perceived risk are appropriately addressed. Key aspects like methodology structure, isolating particular steps and their influence on individual elements and risk specifics, like quantifying explicit elements into comparable and easily understood metrics are instrumental aspects of effective risk assessments, particularly in the risk averse industrial sector. As a result, influential methodology structures and designs in addition to industry proven techniques including risk assessment and criticality ranking processes are evaluated in the following sections. Overall, the intention of this section is to highlight and discuss these influential aspects to provide a deeper understanding of the topic based on the relevant literature and provide confidence in future frameworks based on these previously implemented examples.

2.3.1.1 Methodology Structure and Design

There are a number of established and widely deployed methodologies for asset categorisation, prioritisation and ranking in practice throughout industry and the wider sectors. As a result, it
is important new methodologies or adaptations of existing examples are robust and reliable for their purpose based on previous assessments, defined guideline documents and current best practices. One methodology structure that forms the basis of many successful implementations and strategies is the Design of Experiments (DOE) methodology. This originally became popular in practice for optimisation purposes, particularly in the chemical industry where numerous parameters must be tuned simultaneously and the system cannot necessarily be described with a set of mathematical equations [163]. The DOE process can also be considered as a robust design methodology to identify the optimal tuning parameters using the minimum number of experiments or iterations. Its aim is to systematically highlight the relative contribution of each tuning parameter on the systems performance and determine the optimal settings to maximise or minimise the desired criterion [163]. Furthermore, this popular optimisation technique can efficiently reveal the influence of defined inputs on selected outputs of designed studies, models or evaluations in practice [164]. The inherent ability to solve complicated problems, while reducing time and resource costs through minimising the required iterations but still obtaining all the necessary information, make this technique universally attractive [165]. As a result, this methodology can provide an effective structure for new methodologies or frameworks that follow its structured, systematic and efficient design, where each output affects the next iterative process step and an industry-recognised approach would be beneficial to its overall success.

The DOE methodology has been applied in a variety of situations but generally, it has shown particular prominence in the pharmaceutical and medical sectors. It has widely been used to understand the effects of multidimensional and interactions of input factors on the output responses of pharmaceutical products and analytical methods [166]. In this study, the DOE methodology provides a clear approach to efficiently identify and explain how critical parameters affect the analytical method performance characteristics. The DOE methodology has also been applied in more process testing and manufacturing applications. With one example implementation used to improve the efficiency of an in-house ultrafine condensation particle counter. In this case, it allowed specific results and key influencing factors within the process to be determined from only thirty one test points with varying operational conditions [167], further demonstrating the value of DOE for applications requiring rigorous systematic approaches suitable for the industrial sector. In the manufacturing sector, this technique has also been applied to optimise energy and waste during the production of 3D printed parts. The DOE approach allowed for efficient process optimisation considering scrap and part weight,
energy consumption and production times. Through the efficient systematic analysis of these variables and the highlighting of the key influences it was possible to reduce the undesirable factors and increase the efficiency of the overall 3D printing process [168]. Following the DOE methodology, it was identified that the slice orientation, or part footprint, was the most influential parameter on 3D printing scrap and that optimising this parameter could reduce scrap weight by 83.3% and 24.5% for single edged notch bend and tensile test parts respectively. This methodology has also been successfully implemented in the energy and power sector. In one particular study, to test environmental variables systematically and outline their statistical influence and interaction with power systems. This enabled utility regulators to evaluate the impact of specific variables efficiently and ensure decisions on environmental factors and revenues were chosen fairly against an appropriate benchmark [169]. From each of these multi-disciplinary examples, the DOE process demonstrates clear advantages and represents a very robust and industry proven methodology that novel systematic frameworks can draw upon to ensure confidence in their process and future application.

Other methodologies in this area have followed a similar approach and equally benefited from the systematic and industry suitable approach. The evaluation of energy flexibility and load shifting potential in the industrial sector has received some attention in the literature, in most cases following a systematic methodology approach to capture the integral aspects of this topic effectively. One study demonstrates a methodology to identify and characterize the available energy flexibility measures in industrial systems regardless of the task they perform in the facility. The main intention is to provide industrial enterprises with a qualitative and quantitative understanding of the capabilities of their industrial systems for energy flexible operation [129]. This study highlights important aspects for evaluations of this type, although it does not consider risk levels or incorporate tacit knowledge from onsite experts, which can be crucial in the risk averse industrial sector to overcome the perceived risk factor that was identified as a key barrier for this topic. This example also lacks the final implementation phase and value generation from an actual demonstration of this methodology in practice, however, in theory it does support the systematic methodology approach required for implementations in this sector and for these specific evaluations. Another study in this area presents a staged methodology to determine the load shifting potential of small and medium sized manufacturing companies [170]. This study demonstrated that the technical load shifting potential of a selection of small and medium sized German companies could reach up to 35 kW and 848 kWh per day. In this case, the lower value still represented 1.2% and the larger value was found to
be 5.1% of the respective site’s average daily energy consumption [170]. This study demonstrates the value of effective evaluation methodologies on industrial sites; however, it only targets load shifting potential and no other DR programme capabilities. Furthermore, the inclusion of production assets and schedules may negatively influence its uptake and acceptance in the risk averse industrial sector, which was also identified as a barrier to adoption in this area. These relevant examples clearly demonstrate the value of these systematic methodologies and evaluations, however they also highlight that further implementations are required, particularly to include and capture more analysis of the perceived risks and benefit of scaled up engagement with this topic in the future.

2.3.1.2 Risk Assessment
Another crucial aspect of previous studies and practical implementations identified in the relevant literature is the concept of risk assessment. Managing and accurately assessing risk is an important aspect of all projects and methodologies, especially when dealing with intellectual or physical value [171]. The ISO publish and maintain one of the most prominent and robust standards in the area of risk management, entitled ISO 31000 Risk Management - Guidelines [172]. This document provides guidelines on managing risk faced by organisations in any context, providing a common approach to manage any type of risk, throughout the lifecycle of any activity or decision-making process in any industry or sector. The detailed principles of this standard, and the supplementary guidelines and techniques outlined in ISO 31010 Risk Management – Risk Assessment Techniques [173], provide the basis for organisations to face all types of internal and external risk factors. Risk assessment and management practices can be found across the industrial sector, showing value with examples from multiple maintenance programs [49] and more specific demonstrations from the pharmaceutical sector [166] to the energy sector [157].

The risk assessment process performs an important role in maintenance decision-making, particularly structuring the process of identifying, prioritising and thereafter formulating effective maintenance strategies. One specific study focused on the suitability of dependability modelling approaches and their treatment of uncertainty when performing risk assessments for maintenance decision making [49]. This review found that within the industrial sector, 21% of the published studies were related to industrial or manufacturing systems, demonstrating the relevance and existing acceptance of the concept in this sector. Another study considered risk assessment in the area of smart maintenance in the industrial sector. This highlighted that dynamic evaluation of the state of the asset in its lifecycle and in the production environment
is essential, particularly to assess the influence of data quality and human decisions on this process [50]. Risk analysis and risk-based maintenance is especially prominent in the chemical industry, where asset failures may cause fires, explosions or toxic gas releases. In one study, a version of the Risk Priority Number (RPN) technique was applied to methodically assess the risk of asset failures on a petrochemical site [174]. This process allowed the 107 assets on the case study site to be efficiently quantified into comparable risk levels and then categorised to highlight the assets identified as the highest risk on the site. The objective asset assessment resulted in 10 assets being defined as semi-critical and 97 as non-critical. This method demonstrated its suitability for use in other industrial applications to categorise assets effectively based on their associated levels of risk.

Risk assessment processes and quantitative demonstrations of risk, like the RPN, are also valuable and commonly found in the pharmaceutical sector [166]. In this example, they are especially important to identify, analyse and evaluate risk that may be detrimental to operations in a quantitative and easily relatable manner appropriate for the industrial sector. Furthermore, risk assessment and management has also shown clear value in the energy sector, through reliability and maintenance applications in the offshore wind industry. The risk and reliability analysis methods allowed for systematic assessment of all variables, incorporating uncertainties and integrating consequences of unexpected events, to support informed decisions [175]. In this study, the Bow Tie (BT) analysis technique was employed to assess the most pivotal risk factors affecting the terminals and ports of an offshore wind turbine system. This allowed for the adequate risk assessment of the systems, despite their high complexity and the numerous uncertainties caused by their extreme site conditions [175]. This risk assessment technique can be valuable for other industrial applications, particularly to capture assessments with multiple factors and quantify the results accessibly for stakeholders from a variety of backgrounds. These industry proven methods have demonstrated success in this area and therefore, would benefit new implementations based on these principles to overcome previous barriers related to perceived risk and a lack of understanding in practice.

2.3.1.3 Criticality Ranking

Another relevant and particularly topical concept in the area of risk assessment and asset categorisation identified in the relevant literature is the process of criticality analysis and ranking. In a similar manner to risk assessment, criticality analysis has considerable influence in areas of maintenance and asset management but also generally across the industrial [50] and power generation sectors [176][177]. Criticality ranking is important for maximising resources
and ensuring the assets with the highest potential failure impacts are clearly identified and maintained to an appropriate standard. This is vital in industries where potential failures may result in catastrophic impacts, however it is important that each evaluation be conducted impartially to obtain suitably representative criticality and risk ratings. When conducting these assessments it is important to consider all influencing factors, with key examples including operational impact, both repair and missed production costs, safety and environmental factors [174].

A prominent technique in the area of criticality ranking is the qualitative calculation of frequency and criticality or Severity vs Probability (SvP) levels [176]. This approach has been successfully applied in the power sector, to improve the felling and pruning programs for overhead power lines by utility companies. The criticality analysis methodology assisted the maintenance measures by optimising the actions to avoid detrimental failures of the lines and transmission network and maximise the application of maintenance measures [176]. In this study, the implementation of this criticality analysis method was expected to provide the business with an annual saving of approximately 33% in overall costs. The value of criticality analysis has also been demonstrated in a power plant application. The results of such an analysis indicated the most critical components for maintenance planners to focus on, thus increasing their overall availability and decreasing the risk to plant operation and any major environmental or grid supply issues [178]. Another analysis, based in the petrochemical industry assisted the categorisation of identified failures into criticality levels. In this case evaluating a failure’s risk to safety and environmental factors, production losses and customer dissatisfaction in order to ensure maintenance actions were effective and reduce overall costs [179]. The added value of this methodology is that it can capture all aspects of risk to the user, from operational to reputational impacts on business value, allowing the user to quantify risk throughout the lifecycle of their infrastructure and processes [177]. Furthermore, the criticality analysis process can significantly reduce the effort and resources required to maintain assets and reduce the human factors influencing risk assessments and decision-making processes to ensure objective and comparable evaluations [50]. The demonstrated success and cross-sectoral applicability of these techniques ensure that they would add industry proven value to new implementations and help to mitigate any perceived risk or hesitancy towards their uptake in the industrial sector. In addition to effective methodologies and risk assessment techniques, suitable modelling approaches can be beneficial to evaluations in the industrial sector, particularly in relation to quantifying potentials and impact. This topic is further detailed in the
following sections as it can also be valuable to reduce believed or assumed risk for practical applications and build confidence through clearly presented outcomes.

2.3.2 Modelling Approaches and Guidelines
An increasingly important aspect in the area of decision-support tools and building confidence in proposed process or operational changes are modelling evaluations and analysis. Modelling can be invaluable as it allows a user to simulate and effectively evaluate any potential impacts virtually before physical or practical changes are implemented. This can be particularly valuable in the risk averse industrial sector, as decision-makers are provided with the opportunity to investigate projects ahead of physical implementation to build confidence and avoid costly issues or unforeseen risk factors. Modelling assets and more specifically AHUs has received considerable investigation and research in the residential and commercial sector, as outlined in Sections 2.2.3.5 and 2.2.3.6. Following the review of the relevant literature outlined in Section 2.2 however, it is evident that there is a scarcity of examples and research outputs in the area of modelling industrial assets to assess the operational risk of their inclusion in DR programmes. Specifically, there is a lack of suitable risk assessment modelling tools to evaluate and demonstrate any operational risk of a suitable industrial asset, like an AHU, participating in DR to minimise the perceived risk and encourage further participation from the industrial sector. A variety of modelling approaches and software packages have previously been utilised to conduct comparable studies on this topic. To ensure previous valuable experience is appropriately captured a selection of modelling approaches and techniques, relevant to this topic are outlined in the following sections. Model calibration and statistical analysis techniques suitable for this application are also discussed in addition to potential software packages and indoor thermal environment standards appropriate for this topic. The overarching intention of this section is to illustrate and discuss the vital and influential aspects in this area, to provide a deeper understanding based on the relevant literature and build confidence in future risk-assessment modelling tools based on these previous approaches and successful implementations.

2.3.2.1 Modelling Approaches and Techniques
Modelling is an important and widely implemented method to evaluate and assess systems and concepts theoretically before implementation or in cases where real world trials may not be possible. Modelling approaches and techniques are present in a number of disciplines and have been utilised for a variety of applications. In this domain, there are numerous concepts and techniques to capture diverse interactions and systems, however most variations fall under the
general concepts of either White Box (WB), Grey Box (GB) or Black Box (BB) modelling approaches, illustrated in Figure 15. WB models are generally physics-based and mechanistic in operation, typically utilising a large number of system parameters or building descriptive parameters in the case of building and thermal system modelling. WB models are fundamentally based on first principles and the conservation of mass, energy and momentum, which require considerably detailed inputs and information on each of the model parameters [180]. As a result, WB models are often time-consuming and computationally intensive; however, they can be very generalisable and provide highly accurate simulation results. BB models are data driven and often use regression or machine learning algorithms to map the relationship between system input and outputs using large amounts of empirical data without the requirement for static system descriptive parameters [57]. BB models are described as data driven as they are generally developed from historical data collected on the system being modelled [181]. The advantage of this is that less domain knowledge is required and it may have greater adaptability as the model will evolve itself with additional new data. The downside of BB models however is their high demand for data, which can be negatively impacted by low quality, missing, wrong or biased data leading to low quality models as well as a lack of interpretability in certain deep-learning based algorithms [180]. Furthermore, being heavily reliant on input data makes them less suitable to predict how a system will perform under scenarios that are rarely or not present in the training data. Thus making BB models less suitable for certain modelling applications assessing scenarios that have not yet occurred or been recorded. GB models have qualities of both WB and BB models and are often called reduced-order or simplified models [180]. GB models, like their WB counterparts, are mechanistic in nature, however the iterative physics-based operations are simplified and aggregated, resulting in a less computationally expensive approach that requires fewer system descriptive parameters [57]. This approach is useful for modelling applications capturing thermal dynamics within the built environment particularly when there is a high level of unknowns or a lack of complete data certainty. GB models are valuable as they can still be applied in cases where there is a lack of detailed information on building phenomena and thermal masses, when there is some uncertainty of the end usage and behaviour of the occupants or when there is limited capacity of the means of calculation [182].
2. Literature Review

Figure 15. Overview of WB, GB and BB modelling systems, highlighting common detail of input parameters [182].

For building simulation, WB models were found to be the most widely used technique in practice. Typically, when utilised with precise building parameters they were found to be reasonably accurate when validated under experimental conditions in building test-cells. These models however, were often found to be inaccurate when compared to measured data from real buildings [57], reducing the levels of confidence they could provide in practice for risk averse applications unless they were suitably calibrated. Further studies in the building simulation domain demonstrate the utilisation of BB and GB approaches to evaluate whole-building heat loss coefficients from large-scale datasets. This study indicates the strong potential to use these modelling approaches to predict these heat loss coefficients in practice however, more research is required before this can support carbon reductions in the existing building stock [183].

Another investigation into the use of BB and GB models to benefit the cost, RES consumption and DR capabilities of a building in the residential sector has also been conducted [181]. The results of this study show that energy savings of up to 32.3%, maximum total peak energy reduction of 39.8% and a maximum cost reduction of 38.1% can be achieved by controlling the heat pump water heater and HVAC systems of a house based on the optimisation provided by these modelling techniques. The DR performance of another residential building’s HVAC system was also investigated in another study, highlighting the suitability of GB models for this particular application and the ability of these resources to provide DR services. In this study, a Resistance Capacitance (RC) model demonstrated that the zone was capable of
reducing its power demand for a DR event by 19.42 to 79.61% across five case study scenarios [184]. This study highlights that RC room thermal models have been utilised and are suitable to capture the thermal dynamics of air-conditioned spaces.

The GB modelling approach has also been demonstrated in other examples for suitable application in the built environment. Another study successfully develops and calibrates a GB model of a naturally ventilated nearly Zero Energy Building (nZEB) to simulate its dynamic internal air temperature profile [57]. This study further demonstrates that this approach is capable of simulating the dynamic internal air temperature profile of these spaces. Moreover, demonstrating that although the GB modelling approach was marginally less accurate, roughly 1.5%, the development time was significantly lower than a WB model, presenting an approximate 90% reduction in human time input. Other studies on this topic have highlighted flexible loads like HVAC systems, in the built environment that can be used for DR applications. One study, utilising internal zone temperature to describe indoor comfort within the zone demonstrates the potential to offer approximately 17% of average heating load as a flexible capacity [39]. This study also demonstrates that the heat load of a thermally light building can be postponed by up to an hour, without having significant impact on the indoor thermal comfort. Further evaluations in the area of utilising mechanically ventilated spaces for DR have been conducted, with an example in a college campus setting offering promising results [185]. Although occupant comfort is often an arbitrary concept, this study, using a survey based on ASHRAE specified comfort zones, demonstrated that the thermal environment was found to be acceptable for more than 80% of occupants during DR events. Furthermore, the testing done on this campus demonstrated that at least a 15% reduction in peak electrical demand could be achieved for DR [185]. These practical implementations and indications of the HVAC potential for DR in the built environment offer encouragement for further participation in this area. Although further research in the industrial sector and demonstrations of performance to minimise the perceived risk barrier are required to appropriately capture the flexible capacities available in this sector.

A particularly relevant technique identified in the area of thermal system modelling and one of the most commonly used GB models in thermal engineering applications are RC models [57]. RC modelling allows for clear depiction and understanding of problem physics and sensitivity to different parameters. It is a well-recognised approach based on the analogy of the relationship between thermal systems and electrical circuits [186]. The relationship between electrical circuits and thermal systems can be used to capture the Resistance (R) and
2. Literature Review

Capacitance (C) of thermal energy flow and storage in a building similarly to those in an electrical circuit [130]. Following this approach, the thermal system being considered can be represented by an equivalent electric circuit that is mathematically identical to the thermal system. This technique allows for simplified and more computationally efficient calculations and evaluations of these systems to be conducted. Examples of its implementation and value can be found in multiple applications across a variety of sectors. For example in the construction sector, where this modelling approach has been utilised to describe the heat transfers within a pipe-embedded concrete radiant floor system to demonstrate its energy and thermal performance [187]. This simple yet accurate heat transfer model allows for the clear energy simulation of the system’s three aspects, the cover, pipe-embedded concrete slab and insulation layer. The cover and insulation layer are simplified as one-dimensional and represented by a model with two resistances and one capacitance (2R1C) and the pipe-embedded layer is captured by a coupled RC model in two parts, describing the heat transfers of the concrete slab and water loop respectively [187]. This simplified RC network provided a clear overview of the system and clearly demonstrates the modularity of this technique and highlights its relevance for further modelling applications.

Additional examples of the value of this technique can be found in the commercial sector, with this approach being applied to the thermal behaviour of a freezer room in a restaurant. This modelling approach assisted the simple demonstration of thermal interactions and calculation of cooling loads in this scenario, allowing its performance to be improved through set point and operational changes [186]. The main output of this study demonstrated that 20% degradation of the zone’s insulation could result in an approximate increase of 15% in the net power consumption by the cooling cycle. In the built environment, this approach has also been used to determine the optimal RC allocation that minimises the heat flux through building walls. Using this modelling approach with three resistances and two capacitances (3R2C), the optimal building RC allocation was investigated in the hot summer and warm winter months of a zone in China [188]. In this study, the proposed optimised RC allocation was capable of providing an approximate 35 to 50% reduction in the accumulated heat loss. Furthermore, this approach has been applied to study the optimal thermal resistance and capacitance of residential building walls. In this case suggesting that the energy efficiency potential can be increased by 6.2 to almost 20.6% in the best proposed case [189]. In another study, an RC modelling approach is utilised to characterise a residential room’s thermal characteristics and evaluate set point and control strategies to optimise its operation for DR. This study demonstrates that temperature set
point control strategies can enable power consumption to reduce during a DR event in the residential sector and that the peak reduction capabilities increase for higher set points, improving more than threefold if the upper limit is increased from 25°C to 26°C [184]. In another study, a 1R1C or lumped parameter model is applied to model the thermal behaviour of a passive house [190]. The simulation of average room temperature was achieved using this technique, capable of predictions with approximately 0.5°C Root Mean Squared Error (RMSE), a statistical analysis metric that will be further discussed in Section 2.3.2.3. This study also demonstrated the ability of this technique to provide a demand prediction for the HVAC, which can provide value for a number of applications. Another study uses a 1R1C model to predict the internal air temperature in a zone and determine the influences of internal gains, including solar radiation, occupants and electrical equipment [191]. In this case, the computationally efficient 1R1C approach was capable of predicting the internal air temperature with total average errors to the measured temperature of 0.25°C for higher and 0.18°C for the lower capacitance scenarios evaluated. These studies demonstrate the applicability of the RC modelling approach for evaluating impacts on internal air temperature, particularly the 1R1C technique, where computational efficiency and modularity are identified as key selection criteria. Overall, these modelling approaches and techniques have demonstrated useful performance in the commercial and residential sectors, which may offer equally as suitable and valuable performance for application in the industrial sector. These approaches may be particularly useful in the case of developing a risk-assessment modelling tool to evaluate and demonstrate any operational risk of a suitable industrial asset, like an AHU, participating in DR to minimise the perceived risk and encourage further participation from the industrial sector in this topic.

2.3.2.2 Model Calibration Techniques

Model calibration and the practical techniques utilised are an import aspect of the practical implementation of modelling approaches outlined in the relevant literature, particularly in the area of HVAC system modelling. One approach, the Morris Elementary Effects method, is often used to select the input factors to be considered in modelling approaches and model calibration. The Morris method consists of calculating the elementary effect for each input factor on each output variable [192]. This assists calibration efficiency and computational workload as variables with minimal to no impact on the outputs of interest can be disregarded, allowing only the critical input factors to be focused on during the calibration process. In one particular study, the Morris method is implemented to reduce the number of input variables
assessed, identifying 69% of inputs for one category of variables and only 15% in another selection, which can drastically reduce the number of variables to be assessed as only the most influential aspects need to be addressed [192]. The Morris method has often been used and is particularly relevant in the literature of HVAC model calibration and sensitivity analysis. In one study, this technique is used during the calibration of an offline automated calibration EnergyPlus HVAC sub-system model [193]. In this example, it was shown that the proposed calibration approach, fixing certain model parameters based on the Morris method, allowed for efficient model calibration without notably affecting accuracy. In another study, this technique was also utilised during the calibration of a whole building energy model for HVAC optimal control [194]. This allowed the four most influential calibration parameters out of twelve to be selected, thus optimising and reducing the computational demand for model calibration.

Another approach for model calibration and sensitivity analysis is the Sobol method [195]. The Sobol method is a variance-based approach to obtain the main and total effects of input parameters using correlation coefficient-based formulae [196]. The main effect of a variable denotes the effect of varying this variable alone, while the total effect of one variable includes the main effect and interaction effects with the other variables assessed. The higher the main or total effect, the more important or influential the independent variable is and if the main and total effect are the same for a specific variable it suggests that the variable has very little interaction effect on the results [196]. This method has been used to conduct sensitivity analysis of cooling demand applied to a large office building, in this case identifying the most influential variables on this load for different locations [197]. In this study, equipment and lighting were found to be the single largest contributors to variance for the London location, accounting for 60% and 40% respectively. The value of this method is demonstrated by its quantitative measure of the influence of each variable, in this study assessing six variables across 20,000 iterations of the building model. The Sobol method can also be utilised to analyse the sensitivity of domestic hot water usage in commercial hotels [198] and the energy performance and thermal comfort throughout building design process [199]. These studies demonstrate the value of this method, however, they also highlight that it is particularly computationally intensive and relatively complex in nature. Additionally stating that it may be more suitable for applications where higher levels of accuracy are necessary or additional analysis of initial values from other methods are required.

The DOE approach, previously discussed in Section 2.3.1.1, can also offer value to model calibration methods. The ability of this approach to identify the optimal tuning parameters
using the minimum number of experiments or iterations can complement the implementation of the Morris method or other approaches to provide an efficient and accurate modelling approach. Further calibration methods and approaches in the literature can be better described as ad-hoc procedures [200], requiring numerous iterations and pragmatic user intervention to tune the model outputs following a manual approach. Another study presents an iterative methodology for the detailed calibration of whole building energy models based on a systematic, evidence-based approach [201]. Following this methodology, and incorporating the version control, iterative change logging and evidence-based approach offer value and confidence to future applications, especially where a systematic and rigorous approach is required. Additional studies have demonstrated the use of empirical data for model calibration, allowing for the best model calibration based on available data and the size of datasets [57]. This study demonstrates that consistent levels of accuracy can be achieved through Calibration (Ca) and Validation (Va) of an internal air temperature model using three out of six weeks of empirical data during calibration and validation (Ca3Va3). The process can also be completed using one week of empirical data for calibration (Ca1Va5) although the accuracy is less consistent; however, it can still achieve acceptable levels of accuracy in certain instances [57]. The empirical data calibration approach has been frequently identified in the relevant literature, with one study implementing this approach to calibrate a commercial building model, including AHU performance for potential DR applications [43]. In this study, the model was capable of predicting AHU performance in a DR test mode with accuracy metrics of -3.6% and 7.1% for normalised mean biased error and cumulative variation of RMSE respectively, variations of statistical analysis metrics that will be outlined in the following section. The model calibration techniques and approaches outlined in this section have demonstrated applicability and suitability to improve future modelling applications. The experience and transferrable knowledge from these examples can be beneficial to future decision support systems and would help to overcome any perceived risk by ensuring confidence in their analysis or produced outputs.

2.3.2.3 Statistical Analysis Techniques for Model Calibration

A number of the previous studies highlighted or identified statistical analysis techniques or metrics in this area during the review of relevant literature [53][58][184][202][203]. Statistical analysis techniques and appropriate metrics are important to ensure the integrity of model calibration and help to demonstrate the accuracy of the model outputs and statistical performance effectively. This allows for a quantifiable and comparable measure of accuracy to
be applied to the model, providing a reliable demonstration of the level of confidence in the results. One metric outlined was the RMSE method [58], adapted for this research as demonstrated in Equation (3). This quadratic scoring rule measures the magnitude of the error between predicted and actual values. In one study, this technique was applied to measure and outline the difference between predictions and measurements during the calibration and final output analysis of a model predicting air temperatures in a naturally ventilated nZEB [58]. Demonstrating a level of accuracy for measurements at room-level of between 0.27°C and 1.50°C RMSE in this case.

\[
RMSE = \sqrt{\frac{\sum (T_z - T_A)^2}{N}}
\]

(3)

The R-squared (R²), coefficient of determination or goodness of fit measure for linear regression methods has also been utilised as a metric in the relevant literature. This technique indicates the amount of variance in the dependent variable that the independent variables explain collectively [202]. This value demonstrates the strength of the relationship between the modelled and the actual values, adapted for this research as shown in Equation (4). This metric was utilised in a study comparing the predictive simulation accuracy between three different building thermal behaviour evaluation tools [202]. In this study, strong relationships were demonstrated using this metric, where values of over 0.9 and maximum values of 0.975 and 0.984 were also demonstrated.

\[
R^2 = \left\{ 1 - \frac{\sum_{i=1}^{N}(T_A - T_z)^2}{\sum_{i=1}^{N}(T_A - T_A^\hat{ })^2} \right\}
\]

(4)

The Mean Absolute Error (MAE) and Mean Bias Error (MBE) techniques were also highlighted as useful metrics to evaluate a model’s output, outlined and adapted for this research in Equation (5). The MAE presents the average of the absolute differences between the predicted and actual values where each of the errors hold equal weighting [204]. The MBE measures the average bias of the results, demonstrating whether the results are skewed in a positive or negative orientation. This takes the average error between the set of predicted and actual values including the positive or negative value of the errors. It should be noted that as this method incorporates both positive and negative values some cancellation could occur. Therefore, this should be taken as more of a general indicator and interpreted cautiously. MAE can range from 0 to infinity in the unit of the variable of interest and MBE from 0 to 100%, as it is converted to a percentage output, each of the scores are negatively oriented, meaning the closer to zero the better. The MAE metric was used in a previous study to demonstrate the
deviation between measured and predicted result from a GB room thermal model, in this case presenting MAE values of 0.1968 and 0.2276 for training and validation data respectively [184]. Another study utilises the MBE metric to demonstrate the accuracy of a model to evaluate passive measures for preventing summer overheating in industrial buildings considering varying manufacturing process loads [53]. In this study, MBE values between -1 and 1.5% for the base model were demonstrated, with values as low as -0.36% for more specific times being studied.

\[
MAE = \left\{ \frac{1}{N} \sum_{j=1}^{N} |T_{zj} - T_{Aj}| \right\}
\]

Finally, another statistical analysis technique used to evaluate the accuracy of a model’s outputs identified was the Pearson’s Correlation (PC) coefficient, adapted for this research in Equation (6). The PC is a measure of the strength of the linear relationship between two variables, for example simulated and actual temperature values. PC can range from −1 to 1, with a value of −1 representing a perfect negative linear relationship, 1 representing a perfect positive linear relationship and a value of 0 indicating no linear relationship between the variables. Generally, a PC value of less than 0.39 is considered weak, values between 0.4 and 0.69 are seen as moderate, between 0.7 and 0.89 strong or high and above 0.9 very strong or very high correlations [203]. In one study, the correlation of phase angle variation and performance for epoxy coatings was investigated using the PC metric. In this case, PC values of between 0.9 and 0.95 were presented, demonstrating a strong to very strong relationship between the variables assessed [203]. Each of the statistical analysis techniques and metrics discussed in this section offer value to their applications, as demonstrated in the examples discussed, in addition to providing confidence and both a quantifiable and comparable metric to demonstrate the accuracy of proposed models. As a result, they can be integral to assist the calibration of future risk assessment modelling tools and to ensure confidence in their potential analysis and results.

\[
PC = \left\{ \frac{\sum_{i=1}^{n} (T_{z} - \bar{T}_z) \cdot (T_{A} - \bar{T}_A)}{\sqrt{\sum_{i=1}^{n} (T_{z} - \bar{T}_z)^2} \cdot \sqrt{\sum_{i=1}^{n} (T_{A} - \bar{T}_A)^2}} \right\}
\]

2.3.2.4 Software Packages for Energy Modelling

There are a number of software packages in the modelling domain, with various advantages and disadvantages depending on their specific focuses and the desired application. Each
2. Literature Review

software package has its own unique system architecture, element of modularity and compatibility, visualisation capabilities, ease of access, potential learning curve for new users and processing capabilities. Examples of numerous software packages and their various applications are present across multiple disciplines and have been demonstrated in the relevant literature. MATLAB [205] is one software package that has shown particular prominence in engineering and thermal environment simulation studies. One such example is its application with EnergyPLAN, an energy-system analysis tool used for the scientific analysis of national and regional energy planning strategies and alternatives worldwide. The tool allows the utilisation of EnergyPLAN in the MATLAB environment, ensuring its computational advantages are captured. This allows the user to easily manage considerably large files, with high resolution annual data, and analyse numerous EnergyPLAN files simultaneously [206]. MATLAB has also been used to design and manage models and simulations of common thermal storage systems in off-grid situations for DSM in nZEBs. In this case, the typical parameters and characteristics of freezers, water heaters, space heating and cooling were combined with solar PV generation and battery storage to develop mathematical models in MATLAB to analyse their performance and interactions within the micro-grid [207]. In this case, the software package demonstrated that it was capable of suitably processing twelve complex algorithms to perform the analysis in this study. Additionally, the MATLAB Simulink tool has been utilised to evaluate the optimal price-based control of HVAC systems in multi-zone office buildings for DR. The detailed mathematical model of this commercial building was used to develop the proposed price-based control strategy using a building’s thermal model and an occupant’s thermal preferences model, to demonstrate its DR capabilities [149]. This study utilised the MATLAB software, however as only a 30-minute time horizon was analysed, its computational efficiency and capabilities were not tested to their limits in this case.

Transient System Simulation Software (TRNSYS) [208] is another software package that has shown prominence in certain analyses and case studies throughout literature. One such example demonstrates its ability to simulate and analyse the key factors of a CHP system within a smart energy network. The TRNSYS model in this case allowed up to 78 components to be captured, including the specific heat-to-power ratios of the major components individually. Furthermore, it effectively outlines how the modelled scenario can meet the electricity and heat demands approximately 12.6% more efficiently than generating heat and power separately [209]. This software has also been used in a study to determine the resilience of different passive cooling control strategies in delivering optimal comfort and energy scenarios in both current and future
extreme conditions, for low energy indoor office spaces. Using a TRNSYS 17 model of an nZEB, the performance of ten passive cooling control strategies were successfully simulated for climatic conditions in two representative cities, Dublin and Budapest [210]. This demonstrated the modularity and processing capabilities of this software, illustrating its value for evaluations on this topic. Another study proposes a flexible energy-building concept based on smart control and high-density latent heat storage that is able to predict the best operational strategy according to the environmental conditions, economic rates and expected occupancy patterns. The proposed smart integration model was successfully developed in TRNSYS and applied to a case study residential building to solve the multi-criteria assessment based on future energy demand prediction, electricity tariff evolution and building performance [138], demonstrating the suitability of this software for this purpose.

Another potential modelling environment utilised throughout the literature is Python [211] the programming language and its encapsulated libraries and developed packages. Python is an open-source programming environment that can capture a multitude of diverse inputs and effectively integrate numerous processes. It has a streamlined architecture and high processing capabilities making it suitable for most modelling applications. Python has previously been used to run machine-learning algorithms and specific programs to forecast and assess the optimal operation of energy systems in the industrial sector. These capabilities of the python software environment assisted the integration of industrial consumers in the smart grid through the load forecasting techniques presented in this study [212]. The Python environment has also been utilised to implement a forecasting model using random forest algorithms for a microgrid system. This allowed the effective analysis of an optimisation study, determining the effects with and without load shifting on scenarios of participating flexible demand resources to be conducted [32]. The resource forecasting in this study was completed using Scikit-learn tools in Python, further demonstrating its applicability and value for modelling studies. Another study analyses the steps taken by the Korean Electric Power Corporation to overcome limitations involved in increasing RES penetration on their national grid. In this case, a prototype of a renewable energy map based on PSS/e and Python was developed to facilitate more practical impact studies incorporating the capacity factors of RESs and automating the screening process for determining suitable interconnection buses and feasible options for grid reinforcement [115]. This study further emphasises the modularity and transferability of this software package for modelling applications. Python has also been utilised to automate the process of setting up and assessing model predictive control algorithms for their application in
buildings, through one of its toolbox extensions called Fast Simulations (FastSim). This example demonstrates the advantages of its modular, extensible and scalable framework provided by its block-based architecture. In this study, the predictive control strategy is used with a decentralised multi-zone GB model as the controller model, which manages to effectively maintain thermal comfort within all zones at minimal system cost [213]. This simulation, run over four months of input data further demonstrates the computational power and suitability of the python software environment for modelling applications.

Modelica [214] is another dynamic modelling language that has shown prominence in this research area. This software has a number of toolboxes that can be implemented and utilised within its solver environment. FastBuildings is a Modelica-based reduced order building model that was designed for supervisory controls and forecasting while TEASER is another example of a Modelica-based package for generating reduced-order models for urban-scale energy modelling [180]. This study however states that Modelica must be customised for individual studies, reducing its compatibility, and generally has an extensive learning curve, making it less approachable for general users. In other examples, Modelica has demonstrated its capabilities as an emulator from which artificially noise-corrupted data can be produced [213]. EnergyPlus [215] and the IDA Indoor Climate and Energy (ICE) software have also commonly been used as building performance simulation tools to varying degrees of accuracy [202]. In this study, a comparison of these two software packages and the TRNSYS software package is demonstrated for the simulation of a phase change material implemented within a solar test box. IDA ICE was demonstrated to present the lowest RMSE, as low as 0.873°C, and highest $R^2$, up to 0.981, values except for internal air temperatures simulated in September where EnergyPlus provided the minimum RMSE value of 2.443°C compared to IDA ICE at 2.652°C. The study demonstrates the potential accuracy of these software packages for applications in this area; however, it also presents the levels of complexity and challenges of implementation associated with maximising their utilisation. EnergyPlus has also been used in studies to evaluate and predict bulk airflow rates in buildings, in this particular case further evaluating a three-node displacement ventilation model in an educational building setting. This study also contributes to build confidence in the use of EnergyPlus to simulate buoyancy driven natural displacement ventilation systems [216]. Demonstrating the increase in bulk airflow by 170% and reduction in internal occupied zone temperature by 1.2°C when the chimney height is increased from one to four meters. With respect to optimising the operation of a building heating system for DR, EnergyPlus has demonstrated the ability to realistically test proposed
control strategies and evaluate the associated advantages and disadvantages of their performance [42]. In this case, demonstrating an approximate 4% decrease in overall cost between a heuristic and optimal control strategy at up to 83% stated accuracy.

Finally, the Hybrid Optimization Model for Electric Renewable (HOMER) grid software [217] has also shown prominence in the smart grid domain. Examples of its implementation include the demonstration of a managed electric vehicle charging station within a simulated microgrid containing connected solar PV and storage in order to assess its economic impact [81]. This study proposes a microgrid strategy that would provide a 139.7% levelised cost of electricity reduction, reducing this from $0.259 / kWh to -$0.103 / kWh. This study also highlights that this software package is only suitable for hourly time horizons and above, which would not provide the resolution for some modelling and evaluation applications. The HOMER software has also been used to specify the technical feasibility of microgrid planning and to select the optimal economic and environmental strategy. Through this software, different scenarios can be considered to determine the suitable capacity of production participants and also assess the reliability indices of the specific microgrid [112]. Each of these software packages have demonstrated their own value and attributes from implementations in the relevant literature, ranging from elements of system architecture, modularity, compatibility, processing capabilities and potential learning curve for new users. These factors help to define and confidently decide on a particular software for a specific purpose and achieve the optimal result in future applications. Overall, it is clear that modelling approaches, facilitated by these software packages, can be vital when conducting rigorous evaluations and can be particularly useful to reduce any perceived risk and clearly illustrate the value generation from decision support and potential risk-assessment modelling tools.

**2.3.2.5 Indoor Thermal Environment Standards**

Similarly to defined risk assessment and criticality ranking structures for risk assessment methodologies, specific standards are crucial to set the ranges, drift limits and provide guidelines for allowable air temperatures where internal air temperature modelling applications are concerned. Defined standards and reliable guidelines are important in all research and practical areas, particularly to build and ensure confidence in a concept or operational process. The area of internal thermal comfort is no different, with three main standards showing specific prominence in this area; ASHRAE 55, ISO EN 7730 and GB/T 50785 [218]. These standards present methods for predicting the general thermal sensation and degree of discomfort of people exposed to moderate thermal environments based on indoor environmental factors.
These environmental factors include temperature, thermal radiation, humidity and air velocity while some personal factors including clothing levels and metabolic rates are also considered. The ASHRAE standard 55 [55] presents details on this topic to specify the combination of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable to a substantial majority (80%) of the occupants within the space. ISO 7730 [56] and GB/T 50785 [219], similarly to ASHRAE 55, present recommendations and guidelines for temperature and thermal environments, however they also break the thermal environment scenarios into three categories. GB/T 50785, which is the Chinese standard for evaluation of thermal environments in civil buildings, also presents requirements for measuring the thermal environmental parameters. This aside, the main differentiator between the standards is that the ASHRAE 55 standard does not have indoor environmental categories but it does define the acceptable, or risk-free, conditions allowable for indoor thermal environments [218]. This factor makes the ASHRAE 55 standard particularly suitable for evaluating processes or influential factors that may influence the operation of AHUs or the internal spaces served by them to determine acceptable limits or quantify levels of risk introduced.

The ASHRAE 55 standard has previously been applied and referenced in a number of studies throughout the relevant literature. This standard was applied in one particular study to evaluate the thermal comfort within a campus classroom setting during room temperature adjustments corresponding to DR events [185]. The practical outline and defined allowable temperature bands of this standard helped to provide structure and confidence in the findings of this study, which demonstrated most notably that the thermal environment in the evaluated classrooms was acceptable for more than 80% of building occupants during the DR events studied. ASHRAE 55 also provides clear detail on allowable temperature drifts and ramps, defined as monotonic, noncyclic changes in operative temperature [55], which can be important for assessments considering operational changes or influencing factors on internal air temperature or HVAC systems. A section of this standard, Section 5.3.5.2, specifies the maximum change in operative temperature allowed over a defined period, as shown in Figure 16. For example to satisfy these criteria, the operative temperature may not change more than 2.2°C during a one hour period and it also may not change more than 1.1°C during any 0.25 hour period within that one hour period [55]. Exceeding these limits may result in an operational risk or unacceptable conditions within the internal space. The local thermal comfort criteria were developed in order to keep the expected percent of occupants who are dissatisfied due to all of
the local discomfort factors at or below 10%, which then feeds into the overall majority of 80% satisfaction when local and operative temperature considerations are combined. Another study highlights the demand side flexibility of an office building case study, using the ASHRAE 55 standard as the levels of thermal comfort that would be defined as acceptable [220]. This study demonstrated that dissatisfaction levels during either of the two flexibility control strategies remained less than 12%, deemed acceptable by the ASHRAE standard, for a one-hour period and therefore found that flexible capacities can be offered by office spaces at low risk to occupant thermal comfort. Another study applies and specifically assesses the temperature drift criteria outlined in ASHRAE 55 during the temperature cycles of direct load control strategies for peak electricity management [221]. Six direct load control strategies were trialled in a university campus setting to determine levels of acceptability, with three scenarios being clearly accepted by the subjects. The results of this study appear to indicate that the ASHRAE 55 defined temperature drift limits are overly conservative, as each of the six scenarios went well beyond the standards limits yet they still yielded high levels of thermal acceptability [221]. This output, while important to understand in the context of this specific study, does further increase the level of confidence provided by other studies demonstrating temperature drifts that remain within the specified limits. Overall, thermal comfort standards and particularly ASHRAE 55 can be beneficial when assessing impacts and any operational risk to internal air temperature. It can provide the additional industry recognised and proven confidence that is vital for risk-assessment modelling tools and their outputs to be accepted in the risk averse industrial sector.

<table>
<thead>
<tr>
<th>Time Period, h</th>
<th>0.25</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Operative Temperature ($t_o$) Change Allowed, °C (°F)</td>
<td>1.1 (2.0)</td>
<td>1.7 (3.0)</td>
<td>2.2 (4.0)</td>
<td>2.8 (5.0)</td>
<td>3.3 (6.0)</td>
</tr>
</tbody>
</table>

*Figure 16. Limits on allowable temperature drifts and ramps as presented in TABLE 5.3.5.3 of ASHRAE Standard 55 [55].*

2.3.3 Conclusions on Influential Methodologies and Approaches

Further evaluation and demonstration of the low-risk DR potential available in the industrial sector, as highlighted in the relevant literature previously discussed, is needed to overcome some of the main barriers to its continued adoption and implementation. A key aspect to mitigate the impact of a lack of understanding, perceived risk and the acceptance of external influences, outlined as major barriers, is to base future frameworks or assessments on industry proven standards and recognised techniques. The previous sections outline some of the key
elements that provide the foundation for future implementations in this area. Based on discussed examples from the relevant literature, the DOE and other defined systematic methodological approaches provide clarity and confidence in the area of methodology and framework structure and design. Defined ISO standards and techniques, including RPN and BT analysis techniques for risk assessment and SvP, among other aspects in criticality ranking have shown prominence in the literature, helping to reduce the potential lack of clarity or understanding further for future applications in this area. Furthermore, appropriate modelling approaches from the literature were addressed including WB, BB and particularly GB approaches. Within this domain, RC modelling techniques were found to be especially relevant for addressing possible risks to internal thermal comfort, with the 1R1C technique found to be suitable for this application and both acceptable and computationally efficient to illustrate any impact for this topic. Model calibration techniques like the Morris method, individually or in combination with other ad-hoc, iterative methodologies were found to be suitable to provide the required confidence in model outputs especially when calibrated with empirical data or evidence-based approaches. Further confidence can be provided through appropriate statistical analysis metrics and techniques, which have been used in the literature to validate and ensure model outputs provide the required levels of accuracy and confidence for the area they are implemented. Additionally, a variety of software packages exist and have been utilised in literature to conduct studies and provide outputs that can help to illustrate and demonstrate the impact or value of a concept effectively. Finally, indoor thermal environment standards, particularly ASHRAE 55 in this area, define the allowable criteria and risk levels for this area, with demonstrations satisfying these stipulations gaining industry proven recognition and the additional confidence provided by this performance. Overall, the influential methodologies and approaches outlined in this section are important foundations for future prescriptive frameworks or risk assessment modelling tools to evaluate and demonstrate the DR potential available in the industrial sector. These industry recognised and proven approaches will be important for future implementations to overcome the barriers of this concept, particularly where any hesitancy or reservations are caused by perceived risk, lack of clarity, understanding or acceptance are concerned.

2.4 Conclusions
This chapter presents a review of the relevant literature in the research field of the industrial smart grid and DR concepts, highlighting the current state of research and the main benefits,
2. Literature Review

Driving factors and barriers to the implementation and adoption of these concepts, as outlined by RO1. Both topics have shown considerable global relevance, while the main benefits attributed to each topic were found to be their ability to incorporate RESs and maintain grid stability, maximising the performance and profitability of existing resources and assisting the reduction of individual site and national emissions. The most common barriers to implementation of each concept generally stem from a perceived risk and lack of clarity and understanding however, the believed cost of implementation, suitable hardware or infrastructure and potential cyber security threats have caused similar hesitation and slowed advancements in this area. Actual and perceived risk was identified as one of the most influential barriers and was present in the majority of papers presenting case studies and addressing the challenges to adoption of this topic. The number of papers specifically dealing with risk in this area, divided into three major relevant topics, of general perceived risk, operational risks and impact on participant or occupants are highlighted in Table 9. From this review, it is clear that any new proposed framework must address each of these topics appropriately to ensure any perceived risk is adequately reduced and this barrier is successfully overcome. The general risk can be mitigated through detailed implementations demonstrating the low-risk potential and valuable impact and benefits achievable through this concept, while the operational risk should be addressed by suitably categorising and methodically assessing assets for their participation suitability. Finally, the impact on participants or occupants can be assessed in advance through virtual, modelling approaches that are based on defined standards and guidelines appropriate for this sector to address this risk factor effectively. A key takeaway from the review of relevant literature was that additional demonstration of successful implementations in the industrial sector would help to illustrate the value and build confidence in the concept. Furthermore, clear demonstrations of the potential impact, low-risk nature and valuable financial performance achievable would help to reduce the barriers and encourage additional participation within the industrial sector.

Table 9. Research papers most clearly dealing with actual and perceived risk, broken into general, operational and impact risk categories.

<table>
<thead>
<tr>
<th>Risk Category</th>
<th>Papers</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Perceived Risk</td>
<td>[36][60][87][110][113][127][135][157][171]</td>
</tr>
<tr>
<td>Operational Risks</td>
<td>[49][50][117][137][166][174][175][176][177][178][179]</td>
</tr>
<tr>
<td>Impact on Participant or Occupants</td>
<td>[41][44][134][142][149][150][151][184][220][221]</td>
</tr>
</tbody>
</table>

The evaluation of existing and emerging concepts and terminologies relevant to this research area and experience from other sectors that compliment, influence and further develop this
topic helped to contextualise the benefits and barriers, while also offering new insights and potential research gaps. A consensus in the literature suggests that a defined prescriptive framework, that addresses operational risks, is required to overcome the main barriers to DR participation in the industrial sector. More specifically, a systematic framework to identify suitable assets for DR participation and highlight any associated risk of their inclusion, appropriate for the industrial sector is required, as currently one does not exist in the literature. This would help to build confidence in the concept, minimise the level of unknowns and ensure sceptical participants are suitably guided through the process. It was also highlighted in the literature that non-critical assets on industrial sites, like AHUs, could be suitable for DR participation and would benefit from further evaluation to capture this potential flexible resource. Furthermore, examples from other relevant sectors identified clear potential that could be transferred to the industrial sector through further evaluation, including HVAC systems, chillers and specific building types, like thermally light buildings. In one study it was presented that these building types may be capable of responding to a DR event for up to one hour with no impact on the internal space [39], however this was only demonstrated on a small scale and therefore, further investigation is required to back up this statement in the wider industrial sector.

Following further evaluation of relevant methodologies, including DOE, risk assessment and criticality ranking, the suitability of these techniques to improve risk-assessment measures in the industrial sector and ensure confidence in their output was illustrated by examples and case studies in the literature. Additionally, the predominant modelling approaches and quantification techniques were evaluated, highlighting their previous implementations in the literature and their embodied value to continued research in this area. These previous examples helped to demonstrate their value for future methodologies and frameworks intending to assess the operational risk of industrial sites participating in DR. The highlighted approaches clearly demonstrate their suitability to assess risk to industrial operations or any impact on internal air temperature within these zones caused by assets participating in any DR programmes. Moreover, the RC modelling technique was shown to be especially relevant for addressing possible risks to internal thermal comfort, with the 1R1C technique also found to be suitable for this application considering DR and both acceptable and computationally efficient to illustrate any impact on this topic. In one study, this efficient technique was found to be suitable for capturing the thermal behaviour of an entire building to within 0.5°C RMSE [190]; however, additional research is required to utilise this on a larger scale in the industrial sector and to
provide a more accurate model for the purpose of DR prediction and risk-assessment. Finally, of the international thermal environment standards, ASHRAE 55 was found to be particularly suitable to define the allowable criteria and risk levels for this area, with future demonstrations satisfying these stipulations gaining industry proven recognition and the additional confidence provided by this performance, vital to overcoming the key barriers to this topic.

The body of research outlined in the remainder of this thesis clearly strengthens and builds upon the existing body of knowledge in this research area demonstrated by the literature reviewed in this chapter. Generally, the results and outputs align with the fundamental conclusion that there is potential for additional industrial participation in smart grids and DR programmes. One identified study comparable to this research, focuses on an optimal price-based control strategy of HVAC systems in a multi-zone office space [149]. This study only considers a single use commercial building, purpose built for this main function however, it does offer valuable learnings and comparisons. In this case, there are comparable DR capabilities demonstrated that also result in minimal impact on thermal comfort, particularly in the lower thermal comfort thresholds. Further similarities can also be drawn from a study investigating the quantification of electricity flexibility in another designated office building for DR [150]. Again, this particular study focuses on a large commercial building, which is not directly relatable to the industrial buildings considered in this research. However, the results of that study also demonstrate the considerable flexible capacities available for DR through a similar approach.

In conclusion, following an evaluation of the existing literature in this area, it was found that there is a knowledge gap and lack of appropriate demonstrations of industrial participation in the smart grid and specifically DR programmes. A defined framework to identify assets on an industrial site, confidently assess and appropriately categorise their associated levels of risk for DR participation is required. This would assist decision makers and potential industrial participants to engage in DR programmes and help them to achieve their identified potential and positively benefit themselves and the wider electrical grid. Furthermore, a simple and transferable modelling tool for industrial sites and their specific AHU and building parameters is necessary to quantify and illustrate important elements influencing the operational risk to internal thermal environments from their participation in DR programmes. This would reduce the perceived risk of their participation and encourage additional uptake, as this was identified and highlighted as a particular barrier to the implementation of this concept. Furthermore, a quantification of the potential flexible capacities available from the industrial sector and
potential impact they may have on the Irish or international electricity grids would be invaluable, as this is not currently well defined in the relevant literature. Each of these new definitions and demonstrations would greatly benefit the overall research area and assist the continued uptake of this concept throughout the industrial sector to the benefit of all engaged stakeholders.
3.1 Introduction

Based on the review of relevant published literature presented in Chapter 2, it is evident that there is clear potential for DR participation in the industrial sector; however, an appropriate framework, including a suitable risk-assessment modelling tool is required to identify the available resource and demonstrate any potential risk of participation. This chapter, highlighted in Figure 17, proposes a defined systematic framework suitable for the industrial sector to comprehensively evaluate the available resources on a site and encourage additional industrial participation based on informed decision-making enabled by its outputs. Furthermore, the formulation and development of an industry specific modelling approach is presented, providing an indoor thermal environment risk-assessment modelling tool to evaluate any potential operational risks for industrial AHUs participating in DR programmes, as an example of one potential asset selected for detailed risk-assessment as part of the overall framework. The risk-assessment modelling tool can be utilised during the initial implementation of this framework if these assets are selected, as a tool to illustrate and verify the risk levels of identified AHUs participating in DR as detailed in this thesis, or applied again in isolation as a tool to assess additional AHUs or configurations following initial implementation.

Figure 17. Overview of thesis, highlighting the current chapter and research objectives to be addressed.

The overall benefit of this framework is its structured approach suitable for this sector, which allows potential participants to identify and present a sustainable portfolio of DR capacity, at an acceptable level of risk including any additional mitigation measures as appropriate, to offer
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flexible capacity to the TSO and benefit themselves and the wider national electricity grid. Moreover, the benefit of this risk-assessment modelling tool is that it allows potential participants to evaluate the performance of an AHU participating in DR, if deemed suitable following the overall framework steps, to scrutinise the potential levels of risk virtually, ahead of any practical implementation or participation commitments. This can be particularly useful in especially risk averse cases, often found in the industrial sector where practical trials may not be possible. Reducing the assumed risk of including these assets in DR builds confidence in their capabilities, helping to advance and encourage additional industrial participation in DR programmes, as outlined in the overall ROs of this research.

3.1.1 Background

The industrial sector accounted for 38% of total global final energy use in 2020 [222], while during the same year the Irish industrial sector accounted for 2,171 ktoe or 19% of national final energy use and 558 ktoe or 22.6% of national final electricity use [15]. As outlined in Chapter 2, there is potential for flexible capacities in the industrial sector and based on these indicative figures, there is value in capturing even a fraction of this resource. The scale of the potential achievable is currently unclear; however, through implementation of a suitable and effective evaluation framework it would be possible to quantify the flexibility potentially available on an industrial site. This could then be scaled up to a national scale to capture the various benefits and help to provide the valuable advantages to the user and wider electricity grid. The available DR potential identified in the residential and commercial sectors detailed in Sections 2.2.3.5 and 2.2.3.6, provide further encouragement as to the possible capacities achievable within the industrial sector. Previous studies identified during the literature review further highlight the potential for DR, load-shifting and flexible capacity in the industrial sector. However, the evaluated studies do not present a methodology or framework, specifically relevant to industrial sites, to review all electricity-consuming assets for both suitability and the operational and perceived risk of their participation in DR programmes. Therefore, it was found that an appropriate framework, incorporating asset identification, categorisation and risk-assessment methodologies and a risk-assessment modelling tool suitable for the industrial sector for one asset as an example, would fill an identified research gap and further advance this sectors engagement and capabilities in national DR programmes. As outlined in Section 2.3.1, the most influential existing approaches for a new framework were found to incorporate elements of DOE, risk assessment and criticality ranking techniques [163][174][175][176]. These established approaches form the foundations and helped to shape the framework
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presented in this chapter, ensuring its rigour and appropriate focus for its specific industrial application.

Following the review of relevant literature, it is clear that modelling tools provide significant value to assessment frameworks and theoretical evaluations of real world applications as the user can simulate and effectively evaluate any potential impacts virtually, before physical or practical changes are implemented. This is particularly valuable within the risk averse industrial sector, as decision-makers are provided with the opportunity to investigate projects ahead of physical implementation to build confidence and avoid costly issues or unforeseen risk factors. Some studies of modelling industrial assets have been conducted, including CHP units and AHU loads to reduce power demand during peaks times, although they did not address the operational risk of including these assets in DR schemes. There are also examples of modelling applications in the residential and commercial sector; however, there is a scarcity of demonstrations and research outputs in the area of modelling industrial assets, like AHUs to assess the operational risk of their inclusion in DR programmes. Some comparable examples have implemented GB modelling approaches to demonstrate certain systems performance, with the RC modelling approach commonly being utilised for internal air temperature modelling and specifically the computationally efficient 1R1C technique, outlined in Section 2.3.2.1. This modelling approach coupled with established industry standards, like ASHRAE 55, offers confidence and helps to mitigate the perceived risk to indoor thermal environments of including these assets in an industrial sites’ DR portfolio. This forms the backbone of the risk-assessment modelling tool presented in this chapter as an example of a commonly suitable industrial asset, outlining this suitability and required rigour to reduce any perceived risk and encourage advanced industrial participation in national DR programmes.

3.1.2 Research Objectives

In Chapter 2, the predominant benefits, driving factors and barriers to the industrial smart grid and DR concepts were identified and discussed. This provided further detail, critical analysis and a better understanding of the research area, in line with RO1, improving the value generated from this thesis and providing a foundation for the remaining work. This chapter aligns with the objectives of RO2 and RO3, to build on these foundations and fill the identified research gap, by defining a novel prescriptive framework and developing a new risk-assessment modelling tool suitable to advance the industrial sectors participation in DR and encourage further engagement from this sector. Examples of previous investigations and case studies have been presented in other sectors or on other assets as detailed in Chapter 2. The industrial sector
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however, has received much less attention with fewer suitable methodologies, frameworks or relevant modelling approaches, thus presenting a number of research opportunities and knowledge gaps that may advance operations in this area. The absence of a prescribed framework to systematically identify, categorise and assess industrial assets for DR participation represents a clear research gap. Furthermore, the lack of a suitable risk-assessment modelling tool to evaluate and demonstrate any operational risk of a suitable industrial asset participating in DR to minimise associated perceived risk, once selected by the overall framework are the focus of this chapter. The systematic framework outlined in this chapter is one of the main novel contributions of this research, captured under RO2 presented in this thesis. The risk-assessment modelling tool and its value to risk assessment evaluations also detailed in this chapter offer another novel contribution of this research under RO3 and further assist the advancement of industrial engagement with and participation in national DR programmes. Finally, the new impact and potential benefits enabled by these contributions will be discussed in Chapter 4 and further detailed in Chapter 5, to satisfy the objective of RO4 and provide a clear, novel indication of the potential value generated from the practical implementation of the concepts outlined in this thesis.

**RO2.** Investigate and formalise a prescriptive framework to advance industrial participation in DR schemes and provide decision support to inform and encourage additional industrial participants.

**RO3.** Develop a suitable risk-assessment modelling tool to evaluate and demonstrate elements that influence the operational risk of a suitable industrial asset participating in DR to minimise the perceived risk and encourage further participation in the industrial sector.

### 3.2 Proposed Framework

To maximise uptake within the highly standardised, regulated and risk averse industrial sector, it is vital that any new frameworks, methodologies or procedures presented are appropriate and evidence based in their design. The benefit of the framework approach, highlighted in Section 2.3 and illustrated in Figure 14, is that the overall framework can capture a number of different methodologies, tools and techniques in each step or over a number of steps to achieve the overarching aim of the framework effectively. To this end, the proposed novel framework outlined in this chapter is based upon existing industry proven approaches and processes, as
previously discussed in Chapter 2, in addition to following a distinct systematic design from its inception to completion, identified as an important factor for success in this area. This efficient, iterative approach and systematic structure was influenced by the DOE methodology, outlined in Section 2.3.1.1, where the quality and completeness of the preceding steps benefit the following steps. Additionally, the Plan-Do-Check-Act approach common in the ISO standards, particularly ISO 50001 [223] and ISO 14001 [224], further influenced the formation of the framework structure. This framework captures all suitable aspects and required stakeholder engagements, another fundamental aspect from the ISO standards, during each step as appropriate for this sector, similarly to the predominant Standard Operating Procedures (SOPs) governing most projects conducted in the industrial sector. The influence and niche requirements of the research area in which this framework is focused are also captured throughout, with the industrial energy-consuming aspects and DR specifics, like quickly shutting assets down, driving and being heavily ingrained within the scope of this framework. A high-level overview of the steps required to identify and categorically evaluate industrial assets’ suitability for DR participation and appropriately assess any operational risk of this in practice are illustrated in Figure 18. This novel framework and its six individual process steps are outlined in detail through Sections 3.2.1 to 3.2.6 of this chapter. Section 3.2.5 will outline the process of developing a suitable modelling tool where one is not available or does not exist, the developed modelling tool will then be utilised in Chapter 4, detailing the case where an existing modelling tool is available. This further demonstrates the modularity of the overall structure and approach, ensuring all industrial assets deemed suitable can be appropriately evaluated within this framework.
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Figure 18. Overview of novel asset selection, categorisation and risk-assessment framework steps.

3.2.1 Step 1 - Define Scope

The first step of this framework forms the foundation of the overall process and ensures its effectiveness through defining the scope and suitably bounding the body of work. Included in defining the scope, Step 1 incorporates brainstorming, discussion sessions, stakeholder engagement and further project formalisation appropriate for the industrial sector. Engaging with all stakeholders and Subject Matter Experts (SMEs) throughout the process helps to achieve a better understanding of the concept and all aspects involved throughout the process. To ensure the integrity of the stakeholder engagement for this work, it is important to ensure representation from at least the following roles, top-level management, which is a key factor in the ISO standards, a facilities, operations, production and maintenance technician and team leader role from each of these departments. This ensures both high level and specific details are captured and considered from every perspective and department relevant to the process. For example, a maintenance technician will be trained in the specific intricacies of maintaining, repairing or replacing the specific assets they are responsible for in their day-to-day role. Whereas a top-level manager, who may not have the same detailed knowledge of specific assets,
can provide information and experience on the maintenance schedules, high-level procurement details and additional vendor relations and knowledge where applicable. The benefit of having representation from each level and the various relevant departments ensures that feedback and suggestions are backed with expertise from many different trainings, experiences and professional backgrounds. Additionally, building a rapport and maintaining communication with each of these stakeholders throughout helps to ensure the successful implementation of the framework.

To improve the value and suitability of the stakeholder engagement and minimise bias, the brainstorming and discussion sessions should be conducted through a semi-structured and silent brainstorming process, incorporating the affinity diagram technique to capture data and categorise outputs [171]. Following the affinity diagram approach, the participants are required to vote from 1 to 3 on their prioritisation of each key aspect or agreement with each decision point to provide a final, quantitative result [225][226]. For this process, voting 1 represents the highest priority and total agreement, 2 medium or some hesitancy and 3 lowest priority or total disagreement with the aspect. To quantify the final decisions, the lowest or joint-lowest scoring aspects are progressed and labelled in green on the final affinity diagram. The remaining aspects for consideration are labelled in yellow and may be revisited following further investigation, while any aspect receiving a vote of 3 is labelled in grey in the final affinity diagram and deemed not worth considering. The core aspects to consider under this framework when defining the overall scope are, if all onsite energy-consuming assets will be considered or just non-production and utilities assets, whether any existing onsite projects or procedures can be leveraged and if all DR system services will be targeted or only specific ones based on suitability [117]. Additionally, it should be determined whether an external aggregator will be contacted at this point and if so, which one and how this engagement will be managed [128]. Following this approach and addressing the key aspects from the outset ensures the user fully captures the entire project and its scope, formalises the intended goals and defines the final objectives in a systematic and well-defined manner.

3.2.2 Step 2 - Asset Identification

Step 2 is the major information gathering stage, where all applicable energy-consuming assets are identified and their relevant information is collected to ensure the complete resource available on the site is captured. On an industrial site, this information is generally found through facilities or maintenance documentation, advanced metering systems, virtual data repositories and historians or by conducting physical site walks. Through whichever suitable
source available, the goal is to collect reliable information for each asset, including details of their system identification tags, location, metering status, nameplate capacity, transmission system architecture, distribution board connection and the area they serve, as these details directly influence the decision-making process later in this framework. This information is then compiled into an asset register, containing all of the relevant energy-consuming asset’s information as outlined in Figure 19. The asset register’s design is comparable to an opportunity register used to maintain numerous ISO guided systems as well as being influenced by evaluation assessments or checklists utilised as part of a LEED [227] or BREEAM [228] certification. This comprehensive asset register builds a strong and robust foundation for the process, where the greater its level of detail and the quality of its inputs maximise its functionality. As key decisions will be based on this register, the accuracy of its information and quality of its data are vital and therefore ensuring its quality will minimise issues and time spent connecting assets during the final implementation and eventual DR participation of the captured assets.

<table>
<thead>
<tr>
<th>#</th>
<th>Tag</th>
<th>Asset Name</th>
<th>Area/Room</th>
<th>Location</th>
<th>SEU</th>
<th>Metered</th>
<th>Name Plate kW</th>
<th>Average kW</th>
<th>Serving</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Exa</td>
<td>Example1</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

*Figure 19. Illustration of the asset register template to capture identified asset information.*

### 3.2.3 Step 3 - Asset Categorisation

Once all applicable assets have been identified and compiled into the register, each asset is then categorised in Step 3. The assets are evaluated according to suitability criteria including rated power capacity, ease of access and complexity or cost of inclusion and then assigned a categorisation from Level 1 to Level 5, as outlined in Table 10. The process is similar to many maintenance procedures found on industrial sites and is comparable to some existing examples, as detailed in Section 2.3.1.3. The suitability criteria outlined in Table 10 were developed as part of this work, based on experience and from previous studies [49][108][117][229], which were then endorsed through engagement with a number of currently operating international DR aggregators, discussions with several specific asset and process SMEs and relevant prospective participants as part of this research. The categorisation process effectively breaks down the entire portfolio of energy-consuming assets on the site into groups, ensuring only the suitable assets are progressed through the remaining steps, minimising time spent on unsuitable assets. The detailed asset categorisation process, in addition to being a fundamental step of this framework, also provides a structured roadmap for continual improvement and progression for the participating site, influenced by the ISO standard’s heavy emphasis on continuous improvement.
improvement. By maintaining an up-to-date version of this asset register, the user will always have a categorised list of assets available for DR participation. As assets are progressed up through the levels, either through their relocation, significant process changes occurring, alterations to SOPs or through capital becoming available to advance their suitability for inclusion, the register will clearly capture this. By utilising the asset register, the user will always be aware of their current portfolio available for electricity market participation, allowing them to fully benefit from their aggregated flexible capacity and maximise their performance.

Table 10. Description of asset categorisation levels utilised in Step 3 of the framework.

<table>
<thead>
<tr>
<th>Level</th>
<th>Category Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Large reliable capacity, negligible to no impact on the end use and suitable access to warrant inclusion</td>
</tr>
<tr>
<td>2</td>
<td>Meet all criteria except capacity not large enough to warrant inclusion at this time</td>
</tr>
<tr>
<td>3</td>
<td>May be included once minor change to process/SOP, cost or location/complexity occurs</td>
</tr>
<tr>
<td>4</td>
<td>Not included unless major change to process/SOP, cost or location/complexity occurs</td>
</tr>
<tr>
<td>5</td>
<td>Do not meet any of the criteria and would not be suitable</td>
</tr>
</tbody>
</table>

To maximise a site’s flexible capacity contribution, additional assets from the Level 2 category such as certain non-essential pumps or fans could also be moved to Level 1 if their electrical feed was co-located or in close proximity to other participating assets. Often a number of smaller assets are deemed infeasible for inclusion due to the additional complexity and labour required to incorporate them into the response portfolio or the additional hardware required not being cost-effective based on their individual capacity contributions. In fact, one of the main considerations and factors in deciding an existing asset’s suitability for DR is the location of its electrical feed. Assets that are supplied by the same electrical panel or bus bar are most suitable for DR as this minimises the need for additional hardware and communications equipment to facilitate their participation. For frequency controlled DR, generally a single mains supply frequency-monitoring device is placed on the participating site within the specified electrical panel to send the shutoff signal to the assets when required by the grid. Due to the tight time constraints and importance of quick, validated responses, these devices must be located as close to the main responding assets as possible. Therefore, in the case of a number of assets responding as an aggregated capacity, the ideal or most suitable case would be that the assets are all supplied from the same electrical panel. This does not mean that sites with dispersed assets should be discounted however, as there are methods to incorporate assets in
3. Methodology

this situation albeit with additional complexities and capital costs. The simplest of which is to install additional monitoring and signalling hardware on each applicable electrical panel but there is an additional cost and this will influence the overall feasibility and cost-effectiveness of the site’s participation. Another option is to install advanced communication devices to relay the signal from the main device to each of the other responding assets. This is a more cost-effective method but can incur issues based on the distances between responding asset electrical panels, communication protocols within the industrial environment and the validation of response performance requirements. These solutions do increase the ability of certain sites to increase their response capacities, particularly if industrial AHUs serving office spaces are their only Level 1 assets and the specific offices are dispersed across vast industrial complexes.

These additional flexibility options may facilitate the participation of other assets initially ranked in the higher levels, like non-office space AHUs that may or may not be co-located on electrical panels to increase capacities achievable with further changes to operating procedures or through the placement of additional monitoring equipment to increase the site’s flexible capacity contribution. To increase available capacities even further, certain compressors or chillers for example may also be suitable for inclusion in response portfolios, whether they are initially classified as Level 1 or higher in practice. It is likely that for legacy equipment this will only be able to happen if the buffer tanks are capable of safely maintaining un-interrupted supply throughout the duration that the compressor or chiller is turned off for response. Although with more sophisticated systems, incorporating integrated stepped controls or variable speed drives, larger or more adaptive capacities may be achievable. In the case of AHUs, variable fan speeds or advanced controls may allow for reductions large enough to warrant inclusion in DR without shutting the asset off entirely. However, this strategy may not be capable of achieving the response time required to participate in the fastest DR categories and therefore may not be as lucrative for the participant, although it may still be seen as an additional risk mitigation option for large industrial AHUs. This may also be the case for some compressors or chillers on industrial sites with suitably advanced control systems, as these systems could facilitate electrical demand reductions without fully shutting the asset off for the response duration. This would ensure the system or buffer tank is still being partially supplied, eliminating instances where it would not be feasible to shut the asset down entirely for DR for any amount of time. This aspect may be further investigated and risk-assessed using a new or existing modelling tool as part of Step 5 of this framework, as a future extension of the current research. The feasibility of this concept would be influenced by the participant’s willingness
to incorporate these assets into their DR response portfolio and the availability of smart control systems to facilitate and control their inclusion; however, these advanced controls would further reduce any perceived risk or barrier to their inclusion.

3.2.4 Step 4 - Risk Assessment and Analysis

In accordance with the framework’s modular and efficient design, based on the DOE process where the most influential aspects are prioritised, only the assets categorised as Level 1 are advanced for further individual risk assessment and in-depth analysis during Step 4. In this step, each of the suitable assets are evaluated using three of the risk assessment techniques presented and endorsed by the ISO standards [173], namely the RPN, SvP and the BT analysis techniques, as shown in Figure 20. These techniques are partially adapted from a traditional focus on general risk to a more defined and specific scope of risk caused by inclusion and participation of the asset in DR programmes.

Drawing on established and industry proven methodologies, the RPN criteria headings of Safety, Environment, Operational and Detectability, were chosen to comprehensively evaluate any risk of each asset participating in DR programmes [50][174]. This ensures each factor is fully considered under each of the specified headings, allowing its potential impacts to be quantified with a comparable and fully representative figure. In addition to the specified

![Figure 20. Flowchart of risk assessment and analysis carried out during Step 4 of the framework.](image-url)
headings, the analysis criteria for this process were adapted and defined for this purpose based on guidance from the relevant international standard, ISO 31010 [173]. These criteria, focused on risk of DR participation and the general template for the RPN analysis are illustrated in Figure 21.

<table>
<thead>
<tr>
<th>Asset</th>
<th>Safety</th>
<th>Environment</th>
<th>Operational</th>
<th>Detectability</th>
<th>RPN</th>
<th>Risk Priority Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex. 1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Ex. 2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 21. Template and defined risk priority ranking criteria for RPN assessment.

The next technique, SvP matrix analysis offers a structured means to evaluate and combine qualitative and semi-qualitative ratings of severity and the probability of occurrence to produce a quantitative risk rating [173]. The increasing scale helps to highlight significant risks and ensures each rating is comparative regardless of asset or process specifics. As part of this framework, this technique is directly focused on DR participation and shutting the asset off for this purpose rather than just a general risk assessment. The severity and probability rankings defined for the implementation of this framework and its specific purpose were formulated based on the prevalent ISO standard [173] and experience from previous study interpretations [174], as shown in Figure 22.

Figure 22. Template with ranking criteria for SvP assessment and analysis.
The third technique, BT analysis, provides a clear diagrammatic method of describing and analysing the extent of a risk from causation through to consequence, illustrating the complete lifecycle of the associated risks, prevention controls and mitigation measures [175]. Visually representing the analysis of potential risks of the asset being shutoff for DR and highlighting each of the factors under the appropriate headings; Sources of Risk, Prevention Controls, Mitigation Factors and Consequences, can be invaluable when engaging in discussions with stakeholders, as it helps to provide a clear and detailed overview of the study and particular asset in question. On completion of Step 4, it is possible to select assets for participation in electricity markets confidently based on the completed evaluation, illustration and analysis of the perceived risks associated with each asset’s participation. Each of the risk assessment techniques provide a complete overview of potential impacts of an asset participating in DR, allowing the user to make an informed decision on their inclusion based on the quantitative outputs of this framework. In the following step, the selected low-risk assets are modelled to reduce any remaining perceived risk further, before they are committed to participate in DR.

3.2.5 Step 5 - Modelling and Evaluation
Step 5 is the last phase of the risk assessment process conducted as part of this framework, where individual or multiple assets are further evaluated for any operational risks caused by their participation in DR. For assets where no risk is identified, receiving both a RPN and SvP score of 1, they can be progressed to the next step immediately, however if any risk is identified and the asset has received a RPN or SvP higher than a 1 then further investigation is required. Following this investigation, if the identified risk cannot be adequately mitigated then modelling of the asset is required to address this risk factor appropriately. This step is particularly beneficial for implementations in the risk averse industrial sector, as it allows the potential participant to investigate and quantify any potential risk virtually before physical resources are used, work is conducted and ahead of the asset being committed to the DR programme. This step consists of modelling the selected asset and the relevant impacts of its operation to evaluate its suitability and demonstrate the low risk of its inclusion in DR individually or as part of an aggregated response portfolio. In practice this evaluation can be conducted as part of the framework’s systematic steps or upon completion, it can be viewed in isolation as a tool to verify the low risk of including other additional assets. Following the framework’s modular approach, a modelling tool can be developed at this stage or one or more existing modelling tools can be utilised based on the specific assets identified on the site upon which this framework is being applied. In the case of industrial AHUs, a specific modelling
approach was developed, as outlined in the following sections, which provides a new, industry-ready tool for conducting indoor thermal environment risk assessments and highlighting suitable mitigation measures. For other assets that may be identified on industrial sites, a different modelling tool can be developed based on the requirements and intricacies of the assets operations. In practice different modelling approaches, from WB to BB may be the most suitable depending on the asset and what is being modelled as the potential impact caused by DR participation. This step allows the user to thoroughly evaluate the performance of an asset participating in DR schemes and scrutinise the levels of risk virtually, before any real-world implementation is conducted. This helps to build confidence in the selections before any significant capital is spent or physical hardware or system changes are implemented. The modelling tool’s ability to perform detailed analysis virtually can also be transferred to other industrial AHUs, due to the nodal and scalable approach, allowing the user to analyse additional assets and grow their aggregated capacity while maintaining control and visibility of any operational risks this expansion may incur. Following this approach and conducting continued analysis can present further insights to assist the progression of future assets or onsite works that may benefit a sites ability to perform and benefit from future DR participation.

3.2.5.1 Overview of Modelling Approach

The objective of the modelling approach outlined in this section is to develop a suitable modelling tool to evaluate any operational risk of an industrial asset participating in DR programmes. AHUs were selected as a suitable asset to develop a new modelling tool and demonstrate the application of this framework step, as they are prevalent throughout the industrial sector and were identified as suitable assets on an industrial site to participate in DR programmes. Additionally, from the review of relevant literature in Chapter 2, no risk-assessment modelling tool for these assets with the specific purpose of assessing any operational risk of participating in DR programmes was found. Therefore, to fill this research gap and satisfy the ROs, it was essential to develop a new modelling tool that would evaluate the impact of responding to relevant GFEs and to assess how this would affect the participant, in order to mitigate any perceived risk. To investigate the possible operational risks associated with industrial AHUs, particularly those serving offices and regularly occupied spaces, interacting with the grid, an offline simulation based modelling approach was adopted, given the barriers to trials and field investigations on live industrial sites. The primary barrier to overcome is the hesitancy of industrial sites to deviate from regular practices or to conduct physical trials of new operating procedures. This often discourages industrial sites from
initially engaging with external DR aggregators or participating in DR programmes at all. The results of a modelling assessment however, provide quantified outputs of the low-risk potential available from the site, allowing decisions to be made based on numbers, assets and a context familiar to the site. This helps to overcome some unknowns that can be barriers to progression and provides a more tangible context for the decision-makers onsite to move forward with selected assets and potential flexible capacity contributions confidently.

Following the review of relevant literature in Section 2.3.2.1, a mechanistic 1R1C air temperature model suitable for industrial building office spaces coupled with a simplified thermal energy model of an AHU appropriate for this purpose was developed. The model is manually calibrated through an iterative process, using empirical data obtained from in situ field measurements and staged input variable tuning from accurate building survey details. The calibrated model is then employed with varying combinations of grid event data, climate boundary conditions and building-system configurations to map the thermal comfort risk topology associated with potential episodic grid driven AHU shut downs. This utilisation evaluates the effect and illustrates any possible impacts of shutting off an industrial AHU in response to GFEs that are designed to maintain the balance of the national electricity grid. This relationship between the industrial site and the national grid is illustrated in Figure 23, where the demonstrated risk evaluations clarify whether the AHU capacity is available to respond. This highlights the use case for this modelling tool to conduct offline risk assessments based on the times that previous actual GFEs would have signalled the AHU to shut off or potential future shutoff times, to demonstrate the low risk of their continued participation in DR programmes.

Figure 23. Overview of grid and building response relationship, outlining potential scenarios and the context of the risk assessment.
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3.2.5.2 Selecting an Appropriate Software Package for the Modelling Tool

Due to the numerous technical requirements and various intricacies of the modelling approach for this application, it was vital to select a suitable software package capable of comfortably meeting each of the specific demands. One of the integral factors for consideration was the computational strength and processing power, as multiple simulations would be required to be run with a variety of different variables within short timeframes. Furthermore, compatibility and modularity of inputs and outputs were also vital to ensure the various data files and information sources could be read in and extracted seamlessly. This was also important to ensure the transferability and compatibility of the developed tool for future work to advance and build upon this research. The suitability and applicability for the intended purpose and access, whether open source or not, was also important to consider during the selection process. Finally, the visual outputs and illustrative design elements were factored into considerations as well as ease and availability of access and potential learning curve associated with the specific software package. To ensure a complete search a comprehensive evaluation was conducted, a number of proven packages from academia and industry were considered, including MATLAB, Excel, TRNSYS 18, Python, Modelica, HOMER, EnergyPlus and Engineering Equation Solver (EES). After careful consideration, as outlined by the comparison and evaluation matrix illustrated in Figure 24, Python and more specifically Jupyter Notebooks [230] was selected as the platform on which to develop and instantiate the modelling tool. This was influenced by its significant processing power, simple design architecture, file and dataset compatibility, ease of scalability and transferability, connection to appropriate visual outputs, availability as open source and ease of uptake. These embodied traits ensure this specific software package satisfies the modelling selection criteria and was deemed suitable to complete the modelling aspects of this research.
3. Methodology

<table>
<thead>
<tr>
<th>Software</th>
<th>Access</th>
<th>Compatibility/Future Work</th>
<th>Frontend</th>
<th>Learning Curve</th>
<th>Applicability</th>
<th>Time Step/Processing</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>MatLab / Simulink</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>Excel</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>TRNSYS 18</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>Python</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Modelica</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>12</td>
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<tr>
<td>HOMER</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>14</td>
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<tr>
<td>EnergyPlus</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>EES</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>12</td>
</tr>
</tbody>
</table>

Figure 24. Comparison and evaluation matrix of modelling software packages rated from 1 (best) to 3 (worst) in each category. As outlined, Python was selected as the most suitable for this application having received the lowest total score.

3.2.5.3 Building the Modelling Tool

A systematic modelling approach, based on established practices and existing published studies [39][57][184][186][190][191], was adopted to capture the complex response of the AHU system to various GFE interactions. The main aim of the approach is to adequately reproduce and subsequently predict the internal air temperature ramps within the indoor occupied space being modelled during shut down of the AHU based on a number of defined input variables.

As there are multiple factors involved in such a complex system, a modular nodal network approach was used to capture every variable and allow each interaction to be broken down into the requisite calculations suitable for processing. Employing this modular approach ensured the granular resolution required to capture and analyse specific temperature deviations and the impact of short-term grid events was achievable, thus providing measurable outputs to analyse the perceived risk and demonstrate the suitability of the asset being investigated. The multiple influences and interactions that exist in this area ensured a nodal network approach was required to capture the observed empirical phenomena being numerically modelled fully and accurately. This approach was chosen as it builds on the concept of quantifying the energy balance at discrete time intervals for each of the nodes in the system, allowing for an approximate solution to the continuous functions describing the energy flow through the system. In the adopted approach, the coupled zone and AHU model are spatially discretised into four main nodes, external (boundary condition), internal (the occupied zone), supply and return (providing energy to and from the internal node at each time step). Using the 1R1C approach, the energy and mass balance equations at each node are solved sequentially,
requiring all unknowns at the previous time step for a given node to be calculated prior to moving to the current time step.

The model initialises by reading in the input files, setting specific constants and variables and assigning initial values to model parameters. The base model for calibration comprised of thermo-physical and operating characteristics taken from a representative industrial building. Table 11 details these various model inputs, which can be adapted to different applications. The heating and cooling values are assigned at this point, ensuring the model is constrained to the actual capacities of the building being evaluated. In addition to the above, any variables with fixed operating values are also set in the model, including mass flow rates, operating schedules and so forth. Once this initial phase is complete, a data frame is created to store each of the output values of the process. The model is then prepared to run through each time step iteration at 60-second intervals over a 24-hour period [231]. The one-minute resolution was selected as a trade-off between computational efficiency, a timeframe for discernible thermal comfort changes and a suitable duration to capture the effect of short-term grid events [232][233]. Following initialisation, the model can run the remaining code and complete the full simulation dataset as shown in Figure 25 and Appendix A, Figures A1 and A2. The same code can be used for calibration and scenario analysis, ensuring its modularity and transferability for applications in the diverse industrial sector.

Table 11. Overview of model inputs, AHU specifics, operating schedule and physical characteristics.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Abbreviation</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Time</td>
<td>t</td>
<td>0</td>
<td>s</td>
</tr>
<tr>
<td>Time Step</td>
<td>dt</td>
<td>60</td>
<td>s</td>
</tr>
<tr>
<td>Runtime (1 Day)</td>
<td>rt</td>
<td>86,400</td>
<td>s</td>
</tr>
<tr>
<td>Room Temperature Setpoint</td>
<td>T_SET</td>
<td>21</td>
<td>°C</td>
</tr>
<tr>
<td>Heating Setpoint</td>
<td>T_HSET</td>
<td>28</td>
<td>°C</td>
</tr>
<tr>
<td>Cooling Setpoint</td>
<td>T_CSET</td>
<td>12</td>
<td>°C</td>
</tr>
<tr>
<td>External Temperature</td>
<td>T_EXT</td>
<td>-</td>
<td>°C</td>
</tr>
<tr>
<td>AHU Scheduled Turn On (06:00)</td>
<td>AHU_on</td>
<td>21,600</td>
<td>s</td>
</tr>
<tr>
<td>AHU Scheduled Turn Off (18:00)</td>
<td>AHU_off</td>
<td>64,800</td>
<td>s</td>
</tr>
<tr>
<td>Volumetric Flow of Supply Air</td>
<td>V̇</td>
<td>12</td>
<td>m³/s</td>
</tr>
<tr>
<td>Zone Volume</td>
<td>V_Z</td>
<td>2834</td>
<td>m³</td>
</tr>
<tr>
<td>UA-Value</td>
<td>UA</td>
<td>866.453</td>
<td>W/m²K</td>
</tr>
<tr>
<td>Percentage of Fresh Air</td>
<td>pFA</td>
<td>20</td>
<td>%</td>
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</tbody>
</table>
There are a number of calculations completed at each time step, to complete the energy balance between each of the nodes, with the most significant calculations, Equations (7) and (8), obtaining the internal air temperature, $T_z$, at each time step, $dt$. This formula takes the initial room temperature for the first run and then the value from the previous time step thereafter.

$$T_z(t + dt) = dT_z(t) + dT_z$$  \hspace{1cm} (7)

The result of the energy balance composed of energy supplied, $E_s$, fabric energy losses, $E_f$, and casual energy gains, $E_c$, captures the energy lost and gained for each time step. This allows the model to predict $T_z(t)$, where the change in temperature, $dT_z$, during the current $dt$, is obtained from Equation (8), shown in integral form but summed discretely in the numerical model.

$$dT_z(t) = \int_{t}^{t+dt} \frac{dE_s(t) + dE_f(t) + dE_c(t)}{\rho_A \cdot V_z \cdot C_A} dt$$  \hspace{1cm} (8)
The energy supplied by the AHU, $dE_s$, is calculated from Equation (9) as the product of the density of air, $\rho_A$, the specific heat capacity of air, $C_A$, the volumetric flow rate of supply air, $\dot{V}$, and the difference between the supply air temperature, $T_S$, and $T_Z$ at the particular $dt$. The $dE_s$ value and heating or cooling mode is determined by a check within the model of whether the $T_Z$ is above or below the $T_{SET}$, ensuring the correct $dE_s$ is delivered.

$$dE_s(t) = \int_t^{t+dt} \rho_A \cdot \dot{V} \cdot C_A (T_S(t) - T_Z(t)) \, dt$$  (9)

The fabric energy losses, $dE_f$, value captures the energy losses attributed to the zone envelope and the external surroundings. As shown in Equation (10), this is calculated as the product of $UA$, the $U$ value of the individual building elements multiplied by their corresponding area, $A$, and the difference between external temperature, $T_{EXT}$, and $T_Z$.

$$dE_f(t) = \int_t^{t+dt} U_A(T_{ext}(t) - T_Z(t)) \frac{1}{1000} \, dt$$  (10)

The casual energy gains, $dE_C$, value in this case is attributed to the occupancy, equipment and solar gains within the zone and is calculated as shown in Equation (11). A field-based observational study was conducted to capture the occupant energy gains, $E_{OC}$, and suitable equipment energy gains, $E_{EQ}$, values.

$$dE_C(t) = \int_t^{t+dt} E_{OC} + E_{EQ} + (T_{EXT}(t) + E_{SO}) \, dt$$  (11)

The solar energy gains, $E_{SO}$, in this case were calculated using a solar heat gain factor based on the Glazing Area (GA) per m$^2$ in place at the case study building [234]. Equation (12) demonstrates this calculation, where $E_{SO}$ is found as the product of solar absorptivity, $\alpha$, and the total solar radiation incidence and Solar Heat Gain Factor (SHGF), It, divided by the convection heat-transfer coefficient, $h_o$, all multiplied by the GA. This low-complexity inclusion was considered acceptable as the glazing accounted for less than 10% of the wall area, therefore it was deemed to have a negligible impact. However, a sensitivity analysis was conducted in Section 4.2.6.5 to ensure this decision was adequately justified.

$$E_{SO} = \left( \frac{\alpha \ It}{h_o} \right) GA$$  (12)

### 3.2.5.4 Model Calibration and Validation

Once developed, the internal air temperature model is then calibrated using empirical data obtained from field measurements on the site that this framework is being applied, as shown in
The Calibration step of Figure 25. The base model for initial calibration purposes utilised data from a representative industrial building as discussed. Being a law-driven model relying on the influence of the energy balance equations, a tailored calibration process was employed to obtain sufficient model prediction accuracy. A hybrid of the Morris method [192], detailed model calibration techniques and iterative calibration processes previously outlined in Section 2.3.2.2, were used to tune the model parameters manually. The Morris method has been demonstrated as an effective technique to identify the most influential input variables to a model with the lowest computational cost and has been suggested by previous researchers as an appropriate technique for building-HVAC model calibration, as highlighted in Chapter 2. Once the main influencing parameters have been identified, the iterative process of varying their input values to improve the accuracy and train the model is considerably more efficient and effective for this application. Training and calibrating the model with empirical data from the site on which it is being applied helps to minimise any bias and reduce the risk of overfitting. By individually adjusting the most influential variables and iteratively generating simulated results for each measured day it is possible to improve the model accuracy and reduce error through a systematic refinement process. Utilising the statistical analysis metrics described in Section 2.3.2.3 it is possible to demonstrate the level of error between the simulated and actual temperature within the internal space and to capture which variable adjustments improve model accuracy across the calibration and validation days. An overview of the proposed calibration process is presented in Figure 26, demonstrating the intended systematic process of adjusting a single variable during each iteration.

![Diagram](image)

*Figure 26. Overview of systematic calibration process employed to improve model accuracy.*

### 3.2.6 Step 6 - Trial and Final Implementation

The final step of the framework, Step 6, encompasses the trial of assets, where appropriate or necessary and the final implementation and commitment to participation in the DR schemes
following identification and risk assessment in the previous steps. In particularly risk averse or validation heavy industries, the identified assets may be trialled offline or in a controlled fashion to further demonstrate their low risk of inclusion before committing them to DR contracts. Generally, this is not necessary as the framework captures and outlines the potential risk, however this additional practical trial phase can help to eliminate any hesitations especially in reluctant industries or for new, first time participants. The final implementation aspect of this step takes the outcome of the applied framework and presents a practical flexible capacity figure available from the participating industrial site. This confidently selected figure or aggregated capacity will have a level of risk acceptable to the specific user and will be suitable and easily incorporated into DR schemes to participate in national electricity grids. The aspects identified throughout the framework steps, including the comprehensive asset register, completed risk assessments and modelling analyses can be utilised to advance additional industrial assets quickly to grow DR aggregations and the flexible capacities available to national TSOs.

3.3 Conclusions

The underlying goal of this chapter and research as a whole is to advance the industrial sector’s engagement and participation in DR programmes, therefore increasing the levels of flexible capacity available to the TSOs on the national electricity grid. This aim, in addition to filling the specific research gaps identified in Chapter 2, are achieved by fulfilling the detailed requirements of RO2 and RO3. The proposed framework to advance industrial participation in DR schemes and provide decision support to inform and encourage additional industrial participants provides the structure to achieve these goals in practice. This new, prescriptive framework is suitable for any industrial site, with the asset identification and categorisation process capable of being applied to numerous different assets based on the participants requirements. Industrial AHUs are a particularly common industrial asset that were also previously highlighted in the literature as being suitable for DR, so they were selected for further detailed analysis and risk assessment using a newly developed risk-assessment modelling tool to demonstrate this particular aspect of the overall framework. The developed risk-assessment modelling tool, suitable to evaluate and demonstrate any operational risk of a selected industrial asset participating in DR helps to minimise the perceived risk and provides the foundation to encourage further participation in this sector. The implementation of this complete systematic framework on an industrial site allows the potential participant to present
a sustainable portfolio of DR assets to the TSO to contribute to the flexible capacities required to maintain reliable control of the national electricity grid. An example of this is outlined in Chapter 4, where this framework is implemented on a relevant industrial site further reducing the perceived risk associated with this concept and filling the research gap of actual implementations identified in the previous literature review. Furthermore, the impact and potential value gained from this concept in practice is further detailed in the following sections of this thesis. Chapter 5 then presents the important insights and findings relevant to this sector, in addition to the financial and emission reduction capabilities achievable on an individual site and national scale.
Chapter 4

Implementation

4.1 Introduction

The aim of this chapter, highlighted in Figure 27, is to outline and detail the practical implementation of the novel framework proposed in Chapter 3. The main contribution to the research area of doing this is to provide decision support and an implementation example for potential participants that will advance and benefit the industrial sector’s engagement in DR programmes through a clear illustration of available capabilities. Following this demonstration, the goal is to increase the levels of flexible capacity available from the industrial sector to assist the TSOs to manage the national electricity grids. Presenting the implementation of the proposed systematic framework, suitable for the industrial sector to evaluate the complete resource available on a site will help to reduce any perceived risk and increase the body of knowledge around DR participation in this sector, previously identified as a barrier to advancements of the concept.

![Figure 27. Overview of thesis, highlighting the current chapter and research objectives to be addressed.](image)

This chapter also presents the application of the industry specific indoor thermal environment risk-assessment modelling tool, to evaluate any potential operational risks for industrial AHUs participating in DR programmes. These specific assets, industrial AHUs, were selected for additional risk-assessment, as they are common throughout the industrial sector, were identified as low risk and suitable assets for DR in Chapter 2 and following the formulation of the asset selection, categorisation, risk-assessment methodologies and risk-assessment
modelling tool as part of the overall framework detailed in Chapter 3. Applying the overall framework in this chapter will help to highlight the existing potential on a representative site and encourage additional industrial participation based on the informed decision-making and potential benefits that can be achieved. Moreover, the insights gained and overall results, impact and discussion generated from this implementation will inform the full impact and benefits achievable on an individual site and national grid level, as outlined in Chapter 5.

4.1.1 Background

There is potential for the industrial sector to participate in DR programmes, as detailed in Chapter 2, however elements of perceived risk, a lack of understanding and acceptance of external influences have previously been barriers to the success of this concept. Therefore, additional implementations and successful demonstrations of the low-risk potential available would be valuable to encourage continued engagement from this sector. Additionally, with the manufacturing sector, where the majority of the buildings represented by the case study site are found, making up a significant proportion of the industrial sector’s electricity consumption [15], there is value in investigating this potential further. By capturing even a fraction of the assets present on these sites, like the AHUs discussed in Chapter 3, a significantly valuable resource of flexible capacity may be achieved. As the specific AHUs identified in this study, Constant Air Volume (CAV) systems, are particularly common in this sector, highlighted by their proliferation on the representative case study site, the additional investigation into their DR capabilities and performance can offer value to a large group of potential industrial participants. As previously highlighted, there is generally unease with implementing significant changes or altering SOPs due to the validation culture ingrained in this sector. Therefore, clarifying and investigating the perceived risk of industrial DR participation and demonstrating the low-risk levels of assets like these AHUs responding to GFEs can help to overcome any possible barriers to further implementation of DR in the industrial sector.

4.1.2 Research Objectives

The main contribution and aim of this chapter aligns with the objectives of RO2 and RO3, as described in Section 3.1.2; however, more emphasis is placed on the impact of these aspects and ensuring the outputs help to reduce perceived risk and encourage additional engagement in DR from the industrial sector. Detailing the implementation of the systematic framework and encompassed risk-assessment modelling tool provides a clear demonstration of the framework’s suitability and value to potential industrial participants. As it specifically helps to reduce risk levels and addresses the lack of understanding, which previously had a negative
impact on engagement. The clear outputs and flexible capacity contribution identified following this implementation helps to demonstrate the value and potential benefits achievable from advanced industrial DR participation on both the site and wider electricity grid level. These defined outputs and achievable flexible capacity contributions will form the basis of the impact and benefit analysis in Chapter 5, in alignment with RO4 to complete the objectives and research contributions presented in this thesis.

**RO2.** Investigate and formalise a prescriptive framework to advance industrial participation in DR schemes and provide decision support to inform and encourage additional industrial participants.

**RO3.** Develop a suitable risk-assessment modelling tool to evaluate and demonstrate elements that influence the operational risk of a suitable industrial asset participating in DR to minimise the perceived risk and encourage further participation in the industrial sector.

### 4.2 Implementation of Proposed Framework

As outlined in Section 3.2 of this thesis, the proposed systematic framework provides a defined process for industrial sites to identify and present a portfolio of suitable low-risk assets to the grid for DR participation. To further outline this framework and demonstrate its application in the intended sector, the framework was implemented within a manufacturing site in the industrial sector detailed in the following section. Importantly, this site has a number of significant energy using assets including production machines, utilities assets and generation sources, which ensure it is representative of the wider sector and is a suitable industrial case study site for the application of this framework. The framework steps previously described in Section 3.2, with additional annotations of the specific inputs and outputs of each step are shown in Figure 28, to provide further insight into the process steps with specific relevance to the practical implementation on the case study site. The framework steps for scenarios when an existing modelling tool is available will be completed, using the modelling tool developed in the previous chapter that was outlined in Section 3.2. The following sections intend to demonstrate the suitability, value and effectiveness of the framework and its specific outcomes. Thus, developing the knowledge and experience in this research area and helping to minimise the perceived risk and apparent barriers to advancing the industrial sector’s engagement with and participation in DR programmes.
4.2.1 Case Study Industrial Site

The case study industrial site selected for this research is a multi-national manufacturing plant located in county Cork, Ireland. This particular site manufactures medical devices across two similar industrial buildings containing numerous production, utility and generation assets including two 3 MW wind turbines, two CHP units (400 kW and 250 kW respectively) and a 200 kW solar PV array. This particular site, illustrated in Figure 29, built in 1997 was chosen as a case study to ground this research as the materials and methods used in its construction
and the processes undertaken within it are representative of the Irish and wider international industrial sector. A number of its building specifics and design principles are shared across members of its international organisation as well as being common in recognised industry best practices [126], adding to the generalisable nature of this research. Furthermore, this site is also particularly representative of buildings in Irish industrial estates based on data from the Central Statistics Office (CSO) in Ireland. According to the CSO, more than 50% of the non-domestic buildings receiving Building Energy Ratings (BERs) up to 2021 were constructed before the year 2000 [235], as was this case study building. A significant number of manufacturing and industrial buildings designed and built in this era used similar materials and followed comparable design practices, like the technical guidance documents for Buildings other than Dwellings published by the Department of Housing, Planning and Local Government [236]. These documents defined the design principles, including U-Values, that are required to be met for new constructions and so industrial buildings built around this era would be required to meet the same standards of construction as the case study site [237]. In addition to being physically representative of Irish industrial sites, the case study site has also previously engaged in local industry energy collaborations and is a member of the Irish LIEN. This fact, combined with its certification to several industrial standards like ISO 14001 and ISO 50001 further demonstrate the site’s commitment to continual improvement and highlights that energy performance is important and highly relevant on this site. Having previously engaged in legacy electricity-market schemes with its CHP unit, it was deemed that this site would be well placed to further investigate and demonstrate the advancement of the industrial sector’s participation in DR. The highly standardised validation culture, rigorous evaluation procedures and risk assessment requirements present on this site ensure that any solutions or proposed frameworks are appropriate for application in the tightly controlled global industrial sector.
4. Implementation

4.2.2 Step 1 - Define Scope

To develop this study and advance the industrial sector’s engagement with and participation in DR, the novel framework was applied on the case study site to assess its encompassed electrical assets. Following the prescribed framework steps, the scope of the project was initially formalised through a number of interactions with the appropriate stakeholders, comprising of semi-structured and silent brainstorming and discussion sessions. To capture the discussion outputs and valuable information generated effectively, the affinity diagram technique was employed to categorise and prioritise the session results, according to the criteria outlined in Section 3.2.1, as shown in Figure 30. Through these sessions and their outputs it was decided to consider all energy using assets on the site for potential participation under each of the suitable and applicable DS3 system service categories. Engagement with each of the stakeholders and SMEs, including representation from management level and team member roles in each of the facilities, maintenance, operations and production departments ensured comprehensive insights were achieved throughout the process. The diverse backgrounds and experiences from each of these participants ensured comments were well informed and balanced from multiple perspectives. In this case, the respective training, experience and competence levels of each participant could be tracked and noted from a number of different sources. The training records and competence matrix, which is an important element to
maintain an energy management system for ISO 50001 certification [223], was an example of an up to date record that demonstrated the competence of these participants to provide appropriate inputs and feedback on their respective areas of responsibility and expertise. Maintaining the communication links with each of these stakeholders throughout the duration of the project provided continued relevance and nurtured an environment where any additional feedback or comments could be easily captured to assist the long-term sustainability of the project.

4. Implementation

4.2.3 Step 2 - Asset Identification

The next step of the framework is the main information and data-gathering phase. Through collaboration with the onsite facilities team and maintenance technicians, each of the asset lists and supplementary details were identified, collected and compiled to form the site asset register, as illustrated in Figure 31. By request of the case study site and due to IP rights, only an example of the complete asset register is presented in this thesis for illustrative purposes. As outlined in Section 3.2.2, this asset register captures all of the information required by the framework to ensure that decisions are suitably informed and maintain the success and sustainability of the overall implementation. Additional information and data was collected and

![Affinity Diagram capturing ranked outputs from semi-structured brainstorming sessions with relevant stakeholders.](image-url)
incorporated from the onsite metering system and data historians where available. Physical site walks were then conducted to confirm the documented information and capture any further information not available through the previous documents or on the sites metering system. Inspecting the assets in person assisted the confirmation of their metering status, nameplate capacities, specific location and other identification tags as well as electrical connection intricacies. Tracing each asset directly back to its assigned bus bar or distribution board helped to confirm these details and ensure any future decisions were based on accurate information, as these details in particular are essential when deciding an assets suitability for DR participation. Once completed, the comprehensive asset register was securely saved and backed up on the sites secure document repository. This was also shared with each of the relevant stakeholders to confirm its accuracy, guarantee a representative data repository had been created and to maintain transparency throughout the process.

![Flowchart of asset identification process with an example of resultant asset register capturing the relevant associated information.](image)

4.2.4 Step 3 - Asset Categorisation

Once the asset register was successfully compiled, suitably capturing all of the required information and data, Step 3 of the framework, the asset categorisation process could be conducted. This consisted of assessing each asset under the framework’s defined suitability criteria, as detailed in Section 3.2.3. The main elements of these considerations outlined in the
overall framework were the rated power of each potential asset or the actual response capacity it would be capable of providing if included and the actual location of the asset and its electrical connections, as these have the largest influence on its suitability and value of inclusion. The specific bus bar or distribution board each asset was connected to was important as this directly influenced the ease, complexity and cost effectiveness of its potential inclusion. Clusters of suitable assets on a single board or within close proximity of each other were considered particularly desirable as this minimised the cost and difficulty of setup and integration for inclusion in a DR programme, as discussed in Section 3.2.3. Furthermore, assets with intrinsic system inertia, known lead times, incorporated redundancy or demonstrated ride through capacities identified by onsite SMEs, like certain AHUs and chillers with buffer capacity, were recorded and captured during the categorisation process. Following the systematic categorisation process, a number of suitable assets were identified onsite and ranked as categorisation Level 1, while the remaining assets were classified into their appropriate categorisation levels, as detailed in Table 12.

<table>
<thead>
<tr>
<th>Level</th>
<th>Category Description</th>
<th>Asset Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Large reliable capacity, negligible to no impact on the end use and suitable access to warrant inclusion Meet all criteria except capacity not large enough to warrant inclusion at this time</td>
<td>Selected AHUs, CHP Unit</td>
</tr>
<tr>
<td>2</td>
<td>May be included once minor change to process/SOP, cost or location/complexity occurs</td>
<td>Extraction Fans, Pumps</td>
</tr>
<tr>
<td>3</td>
<td>Not included unless major change to process/SOP, cost or location/complexity occurs</td>
<td>Remaining AHUs, Compressors, Chillers</td>
</tr>
<tr>
<td>4</td>
<td>Do not meet any of the criteria and would not be suitable</td>
<td>Production Equipment, Humidifiers, Lighting</td>
</tr>
</tbody>
</table>

This categorised asset register, part of which is shown in Figure 32 as an example, was then securely stored and saved onsite, ready to be updated appropriately to reflect any relevant changes or updates to the assets that would constitute a change of their initial ranking. In cases where an asset is updated and moved through the categorisation levels or up to Level 1, it will be considered for participation and subjected to further assessment and evaluation as appropriate. These assets can then be included in the sites DR portfolio, based on the completed risk assessments, at the earliest opportunity, ensuring the participant is maximising their available resources and is always aware of the flexible capacities available from their site.
4. Implementation

4.2.5 Step 4 - Risk Assessment and Analysis

The next part of the framework, Step 4, captures the main practical risk-assessment aspect of the process. Once each of the assets have been evaluated and categorised in the previous steps, the Level 1 assets are progressed for this further analysis. In this case, only the AHUs and CHP unit shown in Figure 32 were progressed as part of the framework’s modular and efficient design. The first technique applied during this step is the RPN assessment, in which each of the selected assets are evaluated under the four relevant and most appropriate headings, safety, environmental, operational and detectability. Each asset was assigned a relevant number rating, denoting how detrimental the impact of a failure would be under each of the specified headings, shown in Table 13. Each of the selected AHUs that were subjected to further analysis received RPNs of 2, as the environmental impact was the only potential risk identified in this case. This was based on the possible risk to the thermal environment within the zones served by these assets and the potential increase in CO₂ levels due to the reduced fresh air supplied. This was only deemed a minor infrequent risk however, based on SME experience onsite, therefore receiving a risk number of 2 in accordance with the risk priority ranking illustrated in Section 3.2.4 Figure 21. The remaining categories were also not deemed a risk, as an AHU failure in this case would not be deemed a safety risk. These AHUs do not serve or affect production or operation areas and any failure would be visible through the onsite Building Management System (BMS) and therefore would be continually monitored and easily detectable. The CHP unit in this case received a higher RPN of 4, with minor infrequent risks identified in two category headings. The safety element of a failure of this unit in a live site plant room and the repair requirements posed a marginal safety risk. The environmental risk was attributed to the higher CO₂ production that would result from the separate thermal and electrical generation units operating to meet the same demand previously covered by the single CHP unit. The operational risk was minimal, as there are two other boilers on site capable of meeting the
demand if required. The CHP is monitored by the onsite BMS, similarly to the AHUs, therefore any potential failures would be visible and easily detectable if they were to occur.

Table 13. RPN assessment of selected assets categorised as Level 1 during implementation of the framework.

<table>
<thead>
<tr>
<th>Asset</th>
<th>Safety</th>
<th>Environment</th>
<th>Operational</th>
<th>Detectability</th>
<th>RPN</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHU 1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>AHU 2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>AHU 3</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>AHU 4</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>AHU 5</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>CHP</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

The next risk assessment technique applied when following this framework is the SvP matrix, which is particularly valuable for highlighting significant risk due to its increasing numerical scale. This also offers a highly comparable, single quantitative measure for numerous varying risk factors. The risk of an AHU failing was analysed first, where this particular occurrence received a SvP value of 2, as illustrated in Figure 33(a). This is due to the very low but not negligible severity of a failure potentially affecting the indoor thermal environment within the zone being served by the AHU. More analysis and risk assessment of this topic is required to counteract and reduce the perceived risk in this area. The second factor of this analysis is the probability of occurrence, which in this case is deemed as remote in accordance with the defined criteria illustrated in Section 3.2.4 Figure 22. As the AHU is switched off daily, routinely monitored through the BMS and subject to regular maintenance schedules the likelihood of additional shutoffs causing additional failures was deemed negligible. The SvP of a CHP unit failure was also analysed, Figure 33(b), receiving a marginally higher SvP value of 4. The ability of the two other gas boilers onsite providing redundancy and being able to meet the full demand requirements if needed reduced the operational risk; however, the minor impact of lowered efficiency caused the severity to be ranked as very low. Having to rely on separate generation sources, gas for the boilers and electricity from the grid increases the CO₂ production and financial cost of maintaining supply without the CHP unit in operation. The probability of a CHP unit failing was deemed as rare, based on its existing demonstrated performance capabilities. The value was somewhat impacted by the more complex and less frequent maintenance schedule influence by external factors and specialised requirements that could not rule out minor reliability concerns.
The third and final risk assessment technique required by this framework and implemented on the case study site was the BT analysis. This technique provides a clear diagrammatic illustration of the lifecycle of a possible failure from sources of risk, including prevention controls and mitigation measures all the way through to potential consequences. In both evaluations of the selected AHUs and CHP unit failures, it was found that the existing prevention controls and mitigation strategies were generally adequate to minimise the identified sources of risk, Figure 33. The main consequence of an AHU failure identified was a deviation beyond the allowable internal temperature limits, which can be further evaluated through modelling and analysis to eliminate any perceived risk and actual unacceptable conditions. The next most prominent consequence arising in both evaluations was the potential requirements for additional parts or servicing, which can easily be mitigated further through reviewing maintenance schedules and stock levels of consumables and replacement parts. Furthermore, each of these assets are shut down and started up routinely, on a daily basis for the AHU, so additional degradation or concerns over the increase in shutdown and start-ups of the assets were minimal. Finally, in the case of the CHP unit the increased demand on existing boilers or grid electricity supply is potentially a noteworthy consequence. The impact of this is generally minimal when viewed in relation to its occurrence compared to the carbon offset and financial benefit achieved through the actual participation in the DR programme and DS3 system services, as outlined in detail in Chapter 5. Following the defined framework and the outputs from the risk assessment process, these assets identified as low risk were still deemed suitable for DR participation on this site. The AHUs in this case were subjected to additional evaluation in the next step, modelling and evaluation, to outline and analyse the potential risk of unacceptably affecting the internal air temperature during a DR event fully, identified as a risk for this asset during the risk assessment.
4.2.6 Step 5 - Modelling and Evaluation

Modelling and further evaluating selected assets can be particularly valuable in the industrial sector to further mitigate any perceived risk and ensure an adequate risk assessment is completed for assets that require further investigation as outlined in Section 3.2.5. This allows additional operational risk factors to be evaluated, demonstrating their low risk of inclusion further and helping to mitigate any other risks uncovered through this analysis. For a selected AHU identified as Level 1 during the implementation of this framework, it was deemed necessary to conduct further investigation as it received both a RPN and SvP of 2, which is above the framework’s permitted threshold to progress immediately. As additional evaluation and analysis was needed to understand and mitigate any potential risk of this AHU being quickly shutdown in response to a DR event it was necessary model and further evaluate this selected asset. Therefore, the modelling tool for indoor thermal environment risk-assessment, developed in Chapter 3, was implemented to assess any potential operational risk caused by this asset participating in DR. The CHP unit was not selected for further modelling evaluation and analysis at this point during the case study implementation, as it was undergoing works directed by the case study site, which may affect its applicability and therefore would be re-evaluated and re-assessed upon completion. The selected AHU and internal office space it serves on this industrial site are further discussed and evaluated in the following sections with detailed results also presented in Chapter 5. This will help to demonstrate the implementation
of this framework step clearly and illustrate the potential value and encouragement it can provide to an industrial site considering DR participation.

4.2.6.1 Case Study Building Thermal Characteristics

The case study industrial office space where the model was applied, calibrated and validated is shown in Figure 29, illustrated as the larger office space on the industrial site outlined in Section 4.2.1. The numerous design principles and building specifics shared across this large organisation’s multiple international sites under their defined best practices help to improve the generalisable nature of this study. This particular building, used to investigate the industry-grid interactions, is also representative of a large proportion of buildings in Irish industrial estates and the wider industrial sector as previously highlighted in Section 4.2.1. The building information and specific values for the zone used during the modelling that was conducted in this research are outlined in Table 14. These values were sourced from the building design specifications and where explicit details or values were not available from onsite records they were confirmed or supplemented by the relevant standards and information sources [236][238]. Further to collecting the U-Values and other information points required for the modelling, outlined in Section 3.2.5.3 Table 11, an internal effective heat capacity calculation was conducted to help categorise the zone being assessed and clarify its position in relation to other building types. Following the methodology outlined in the ISO 52016-1 standard [54] and supplementary documents in ISO 13786 [239], the zone was found to have a light internal effective heat capacity. The inputs for this calculation and result are displayed in Table 14.
4. Implementation

Table 14. Case study building information, values and thermal characteristics for modelling and internal effective heat capacity classification.

<table>
<thead>
<tr>
<th>Item</th>
<th>Area (m²)</th>
<th>U-Value (W/m²K)</th>
<th>Material</th>
<th>d (m)</th>
<th>ρ (kg/m³)</th>
<th>C (J/kgK)</th>
<th>Cm (J/(m²K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Wall</td>
<td>445.5</td>
<td>0.3</td>
<td>Plasterboard Insulation</td>
<td>0.013</td>
<td>800</td>
<td>840</td>
<td>8736</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Plasterboard</td>
<td>0.087</td>
<td>35</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.013</td>
<td>800</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td>External Wall</td>
<td>23</td>
<td>0.463</td>
<td>Concrete Block (Lightweight)</td>
<td>0.087</td>
<td>600</td>
<td>840</td>
<td>52,584</td>
</tr>
<tr>
<td>Windows</td>
<td>46</td>
<td>2.476</td>
<td>Carpet</td>
<td>0.02</td>
<td>186</td>
<td>1360</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Concrete Screed</td>
<td>0.05</td>
<td>1000</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cast Concrete (M. Density)</td>
<td>0.03</td>
<td>1200</td>
<td>880</td>
<td></td>
</tr>
<tr>
<td>Floor</td>
<td>944.5</td>
<td>0.322</td>
<td>Ceiling Tile Air</td>
<td>0.016</td>
<td>380</td>
<td>100</td>
<td>608</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Concrete Screed</td>
<td>0.084</td>
<td>1.2</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Ceiling</td>
<td>944.5</td>
<td>0.322</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total UA Value</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>866</td>
<td>W/K</td>
</tr>
<tr>
<td>Zone Volume</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2834</td>
<td>m³</td>
</tr>
<tr>
<td>Total Cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>140,668</td>
<td>J/(Km²)</td>
</tr>
</tbody>
</table>

ISO 52016-1 Internal Effective Heat Capacity Classification

Light

The specific internal space being analysed maintains a consistent Monday to Friday occupancy and regular daily AHU operating schedule. The unit itself is monitored and operated from a central BMS, where the internal, external, mixed and return temperatures can be viewed as well as the percentage of fresh air incorporated and a number of other fan states and operating modes, as illustrated in Figure 35. The low thermal inertia and light fabric envelope characteristics of these buildings, which are representative of office spaces on industrial sites, produce responses to changing AHU behaviours that warrant further investigation. Thus, evaluating the DR potential of this case study site, as it is representative of other AHUs, buildings and office spaces throughout the wider industrial sector, offers novel value to the wider research area.

Figure 35. Screenshot example of AHU control screen from case study BMS, including annotated components and their expected contribution capacities for DR.
The specific components within the AHU considered for DR are also illustrated in Figure 35, namely the supply and return fans and heating and cooling coil circulation pumps. The supply and return fans were focused on to provide the flexible capacities for DR on this case study site as they offered the largest loads, of 10 to 15 kW and 5 kW respectively. The combination of these two components provides the expected flexible capacity directly within the bounds of the specific AHU, defined at 15 kW to provide the most representative figure from the case study site. These components were also found to be particularly suitable for DR as shutting them off produced a linear and consistent energy reduction. This factor avoided the potential challenges of more complex elements that can cause uncontrolled or unexpected spikes in energy consumption post-GFE, which is undesirable from a grid control and reliability perspective. Additionally, these components were considered as they would both be consistently running during any stage of the AHUs operating schedule and so would always be available to shut off for a GFE. Whereas the heating and cooling coil circulation pumps would be influenced by the operating mode the AHU is in at time of the event and so would not always be guaranteed to provide the defined and consistent flexible capacity figure required for DR participation. Furthermore, the energy reduction directly attributable and within the bounds of the specific AHU would not be that large, as only the heating and cooling circulation pumps could be shutoff for the individual unit, amounting to less than 1 kW of flexible load. This is because the hot and chilled water are fed from a communal header onsite, similarly to other installations in the commercial setting [240]. Therefore, the energy reduction for specific AHUs would be confined to only the circulation pumps and not, for example, the entire chiller load supplying the cooling energy at the given time or the larger circulation pumps serving each of the AHUs across the site.

4.2.6.2 Empirical Data Collection

Another element of the modelling step of this framework is ensuring the integrity of the model and the results it outputs. To satisfy this aspect, it is important to collect empirical data to calibrate and validate the model. To collect suitable empirical data for model tuning and calibration, a calibrated Hanwell wireless data logging system, accurate to ±0.1°C between -10°C and 40°C, was used to collect field measurement data. These sensors were used to collect indoor air temperature data within the zone, as the indoor air temperature values are used to calibrate and validate the model. These sensors were placed at six desk level locations, 1.2 m above finished floor level, in the selected open plan office to represent the temperature experienced by the majority of occupants. The locations were chosen to represent the main
occupant areas, with at least one sensor covering a 15 m occupied area anywhere in the zone. Following a review of supply and exhaust diffuser locations, desk layout, perimeter glazing and any other factors that may interfere with the results; the sensors were placed as illustrated in Figure 36(a-c). This was done to collect accurate readings for the overall zone, similarly to the onsite BMS system, minimising the influence of hot or cold spots and ensuring a representative depiction of the internal air temperature within the zone was achieved. The Hanwell system logged the data at one-minute time intervals for each sample location, as specified in Section 3.2.5.3. Using the Hanwell proprietary connection and software, the data was retrieved from the in-situ loggers at four-week intervals. The raw data was cleaned, wrangled and processed in Jupyter Notebooks, part of the Python software, using Pandas to read in the large volumes of data and process each value into a standard format. During the processing, the raw data from each sensor was extracted from the Hanwell storage files into a Pandas data-frame, where each timestamp was aligned, an appropriate naming convention was applied and the units (°C) were confirmed and carried through as necessary for each value. Once the data-frame was suitably prepared, the data was saved into a common .csv file ready to be utilised by the model. Aside from the five-minute gap per sensor occurring during the data collection and resetting process, there was only one significant data drop encountered during the data collection. This occurred in the first week of data collection due to an occupant inadvertently moving one of the sensors within the office space. This was accounted for during data compilation and further mitigated by informing the occupants of the sensors and their purpose in addition to placing extra signage around the sensor devices.
The temperature data collected from the six locations was combined to get an average value for the zone, in the same manner that the internal temperature is monitored by the onsite BMS to send and receive signals from the AHU and internal space. This resulted in a single averaged temperature value for the internal space, which was used for model calibration. Following a review of the sub-zonal temperature variations between each of the six locations, it was found that there was a maximum difference of only ±0.6°C between each temperature reading at the same time step. This was deemed as having a negligible impact across any studied time horizon and particularly for the time interval of any grid event, as the entire zone would not be outside the ranges and the existing site BMS operates using the same averaged temperature value. To fully evaluate and adequately demonstrate the low risk associated with shutting these assets down to participate in a DR event, it was also important to evaluate the impact of various external air temperatures as this measurable variable can impact the internal air temperature of the zone. Both the processed internal air temperature data, for comparison as the $T_A$, and measured external air temperature, as an input variable, were utilised for model calibration.
The external air temperature data was taken from the sites BMS external air temperature archive, drawing data from sensors accurate to ±0.2°C between -20°C and 60°C. Table 15 contains a summary of the field measurements and related external temperature data.

Table 15. Overview of the internal temperature field measurements and external temperature data collected from the case study site for a selected number of days.

<table>
<thead>
<tr>
<th>Day</th>
<th>Date</th>
<th>Internal Temperature Data</th>
<th>External Temperature Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min (°C)</td>
<td>Daily Mean (°C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(hh:mm)</td>
<td>(°C)</td>
</tr>
<tr>
<td>0</td>
<td>5/06/20</td>
<td>21.4</td>
<td>22.1</td>
</tr>
<tr>
<td>1</td>
<td>8/06/20</td>
<td>21.3</td>
<td>22.2</td>
</tr>
<tr>
<td>2</td>
<td>9/06/20</td>
<td>20.8</td>
<td>21.8</td>
</tr>
<tr>
<td>3</td>
<td>10/06/20</td>
<td>21.3</td>
<td>21.8</td>
</tr>
<tr>
<td>4</td>
<td>11/06/20</td>
<td>20.9</td>
<td>21.6</td>
</tr>
<tr>
<td>5</td>
<td>12/06/20</td>
<td>21.1</td>
<td>21.8</td>
</tr>
<tr>
<td>6</td>
<td>15/06/20</td>
<td>21.5</td>
<td>22.6</td>
</tr>
<tr>
<td>7</td>
<td>22/06/20</td>
<td>21.3</td>
<td>22.1</td>
</tr>
<tr>
<td>8</td>
<td>24/06/20</td>
<td>21.1</td>
<td>21.9</td>
</tr>
</tbody>
</table>

4.2.6.3 Model Calibration and Statistical Analysis

Following collection of the requisite empirical data, the model can be calibrated, which allows its accuracy in predicting the internal air temperature on the industrial site on which this framework is being applied to be assessed and quantitatively defined. The model was calibrated using one day of actual measured conditions and validated across the remaining eight days of measured values using the Ca1Va8 process, thereby allowing the model to be trained effectively on empirical conditions whilst minimising bias and reducing the risk of over fitting. As AHUs are generally run on a consistent daily schedule with minimal operational variations, it was found that additional validation days were more valuable than calibration days to gain insights and build confidence in the accuracy of the outputs. By individually adjusting the most influential variables and iteratively generating simulated results for each of the eight days it was possible to minimise model error through the systematic refinement process. The most influential inputs were found to be the $E_C$ both during and outside its operating schedule, the zone volume and hence associate UA values and the AHU start-up hour where its cooling or heating power is slightly reduced. The overview of the calibration process in Figure 37 demonstrates the systematic process of adjusting a single variable, $E_C$ in Steps 1 through 4, UA values in Steps 5 and 6 and the AHU start-up in Step 7, to reduce the level of error in the results.
4. Implementation

This level of error was demonstrated by the statistical analysis metrics described in Section 2.3.2.3, which were applied to assess the model’s performance and indicate the prediction accuracy of internal $T_z$ across the eight validation days in this phase. During the calibration process, the average value for each of these metrics at each calibration step across the eight validation days is illustrated in Table 16. This demonstrates the gradual improvement, or reduction in error, across each value during calibration until acceptable levels for each metric are achieved.

Table 16. Averaged results for each of the statistical analysis metrics across the eight validation days through the iterative calibration process steps.

<table>
<thead>
<tr>
<th></th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 4</th>
<th>Step 5</th>
<th>Step 6</th>
<th>Step 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE (°C)</td>
<td>0.40</td>
<td>0.40</td>
<td>0.30</td>
<td>0.50</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.03</td>
<td>-0.11</td>
<td>0.39</td>
<td>-0.41</td>
<td>0.49</td>
<td>0.46</td>
<td>0.49</td>
</tr>
<tr>
<td>MAE (°C)</td>
<td>0.40</td>
<td>0.40</td>
<td>0.30</td>
<td>0.40</td>
<td>0.30</td>
<td>0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>MBE (%)</td>
<td>1.17</td>
<td>-1.08</td>
<td>0.08</td>
<td>1.35</td>
<td>0.38</td>
<td>0.17</td>
<td>0.22</td>
</tr>
<tr>
<td>PC</td>
<td>0.84</td>
<td>0.87</td>
<td>0.89</td>
<td>0.91</td>
<td>0.92</td>
<td>0.92</td>
<td>0.93</td>
</tr>
</tbody>
</table>

The average RMSE value for each of these days was 0.3°C, with a range from 0.2°C to 0.5°C. This is an adequately low figure compared to similar studies utilising this metric [57][202] and from a thermal comfort perspective it would be relatively indiscernible, meaning this level of accuracy is acceptable for the purposes of this study. The post-validation average $R^2$ value was 0.49, which represents a moderate relationship between the modelled and actual internal temperature values. However, when combined with the other evaluated metrics this was deemed acceptable and suitable for this specific purpose [148]. The MAE was found to be 0.2°C across each of the days, with a range from 0.1°C to 0.4°C. This value, similarly to the RMSE, was found to be at an acceptable level of deviation from observed values for the purposes of this study [184]. The final MBE value was 0.22%, ranging from -1.2% to 1.9%.
This range represents a very low level of error, less than 2% in both the positive and negative direction and therefore was found to be acceptable for this purpose based on comparable studies [58]. The marginally positive bias of the average value was also noted, but deemed acceptable as overheating of the room or the danger of under-predicting the internal temperature was seen as a higher risk. Finally, the PC resulted in an average value of 0.93, with a range from 0.88 to 0.97. The lowest value within this range falls within the strong to high correlation category and the average value is even within the very strong or very high category thereby demonstrating that there is a very strong correlation between the predicted and $T_A$ values [203]. Based on these values and the comparative accuracy compared to other relevant studies, the calibrated model was deemed suitable for the purpose, of evaluating the impact on the internal space if the AHU was participating in a DR programme and demonstrating this potential risk to a potential industrial participant as part of this framework.

### 4.2.6.4 Boundary Conditions and Future Temperature Data

To stress test and evaluate the likelihood of any grid interaction resulting in high risk or unacceptable conditions, where the temperature exceeds the specified ranges or drift criteria, a number of different extreme event boundaries should be explored and will be outlined in Chapter 5. As the case study site is located in county Cork, Ireland, the synoptic meteorological weather station at Roches Point was selected as a representative data source for external air temperature at this site. Thirty years of historical weather data from the nearest synoptic weather station maintained by the national meteorological service were analysed to identify 99th percentile maximum and minimum daily temperatures (hottest and coldest days) and their corresponding diurnal temperature profiles. This analysis identified Monday, the 2nd of July and Thursday, the 1st of March 2018 as the hottest and coldest recorded days, respectively [241]. Formalised datasets of these daily profiles were both used to simulate the AHU’s operation in scenarios with extreme external temperature conditions, thereby evaluating the potential risk of participating in grid events on both ends of the external temperature scale.

The future temperature data used for additional analysis in this research was sourced from Meteonorm Version 7.3.4 [242]. Meteonorm was selected to source the future temperature data files as it outputs .csv files, which were already a common input for the model and so minimised additional coding requirements. Furthermore, an appropriate license was available and this software was designed to generate accurate and representative time series temperature data for any location on earth, making it specifically suitable for this purpose [242]. This predicted temperature data allowed evaluation of potential scenarios for the Cork region in the years 2030,
2050 and 2100 as well as an example of Budapest (BP), Hungary in the year 2050. This example of anticipated Budapest temperature offers insights into how this system might perform in more extreme conditions representative of the wider European climate. As the climate in Budapest presents much more rapid fluctuations from hot to cold and larger temperature ranges, highlighted in Table 17. Additionally, the climactic impact and shape of daily temperature profiles and conditions in 2050 present even further interesting elements worthy of analysis [243]. These datasets were created based on the assumptions of the IPCC AR4 A2 scenario, the most pessimistic or lowest year on year reduction in carbon emissions available for simulation. After more analysis, these annual datasets allowed both the hottest and coldest days in each of the selected years to be extracted and daily profiles to be created. Table 17 contains a summary of the historical data and the predicted future temperature data used in this study. Further analysis can then be carried out including these extreme boundary conditions to generate additional insights, results and valuable discussion from this research.

Table 17. Overview of hottest and coldest daily external temperature profiles used for additional model analysis.

<table>
<thead>
<tr>
<th>Climate</th>
<th>Year</th>
<th>Type</th>
<th>Date</th>
<th>Min</th>
<th>Daily Mean</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cork - Historical</td>
<td>2018</td>
<td>Hottest</td>
<td>02/07/2018</td>
<td>14.7</td>
<td>06:00</td>
<td>19.9</td>
</tr>
<tr>
<td>Cork - Historical</td>
<td>2018</td>
<td>Coldest</td>
<td>01/03/2018</td>
<td>-5.2</td>
<td>03:00</td>
<td>-3.2</td>
</tr>
<tr>
<td>Cork - Future</td>
<td>2030</td>
<td>Hottest</td>
<td>24/07/2030</td>
<td>17.6</td>
<td>02:00</td>
<td>20.4</td>
</tr>
<tr>
<td>Cork - Future</td>
<td>2030</td>
<td>Coldest</td>
<td>27/12/2030</td>
<td>-1.1</td>
<td>00:00</td>
<td>0.9</td>
</tr>
<tr>
<td>Cork - Future</td>
<td>2050</td>
<td>Hottest</td>
<td>21/07/2050</td>
<td>13.3</td>
<td>00:00</td>
<td>19.5</td>
</tr>
<tr>
<td>Cork - Future</td>
<td>2050</td>
<td>Coldest</td>
<td>01/01/2050</td>
<td>-0.6</td>
<td>08:00</td>
<td>1.1</td>
</tr>
<tr>
<td>Cork - Future</td>
<td>2100</td>
<td>Hottest</td>
<td>19/08/2100</td>
<td>16.7</td>
<td>05:00</td>
<td>21.4</td>
</tr>
<tr>
<td>Cork - Future</td>
<td>2100</td>
<td>Coldest</td>
<td>01/04/2100</td>
<td>-1.0</td>
<td>09:00</td>
<td>1.5</td>
</tr>
<tr>
<td>Budapest - Representative of European Climate</td>
<td>2050</td>
<td>Hottest</td>
<td>07/07/2050</td>
<td>27.5</td>
<td>00:00</td>
<td>35.9</td>
</tr>
<tr>
<td>Budapest - Representative of European Climate</td>
<td>2050</td>
<td>Coldest</td>
<td>14/01/2050</td>
<td>-14.7</td>
<td>07:00</td>
<td>-10.2</td>
</tr>
</tbody>
</table>

4.2.6.5 Sensitivity Analysis

To gain a deeper understanding of the model outputs and develop further insight into the level of influence the major input variables have on the results, a model sensitivity analysis was conducted. This analysis focused on the UA-Values and solar gains attributed to the level of glazing present in the zone, which were found to be two of the most influential factors on the modelled internal Tz. To conduct this analysis, two days of external temperature data were selected to form the baseline for comparison. The first day selected was Day 3 of the measured data, shown in Figure 38. The second day selected was the external temperature data for the
hottest day in Budapest in 2050, Figure 39, which provides an insight into potentially extreme external temperature conditions. As shown in each of these figures, a number of results were generated based on a 5, 15, 25, 50 and 75% increase in glazing levels compared to each baseline. For each of the scenarios the UA value of the zone was updated to reflect the changes made to the glazing areas. As illustrated in Figure 38, the Day 3 temperature data shows that the zone was noticeably cooler outside of the AHU operating hours due to increased losses caused by the modified UA values and effect of no solar gains during the cooler night time period. Additionally, it is clear that there was minimal impact to the indoor thermal environment caused during the AHUs operating hours across each of the scenarios, as there was never more than a 0.05°C deviation from the baseline at any stage.

![Figure 38. Daily internal air temperature profile for model sensitivity analysis of Day 3 data, with AHU operating hours highlighted by green shaded area.](image)

A similar result was found when evaluating the Budapest data, Figure 39, although the zone was marginally hotter outside of the AHUs operating schedule caused by the increased heat gain from the higher external temperatures and differing UA values of the zone. This impact along with the increased solar gains visible during the AHU’s on period is further illustrated by an increase in internal temperature during the extreme heat of the daytime hours. Although again this does not have a major impact on the model performance, as the deviation in temperatures even in this extreme scenario do not exceed 0.12°C. This does not influence the case study site building being evaluated, but it does offer valuable insights for future implementations of this research both nationally and internationally, given the representative nature of the case study building.
In industrial office spaces with considerably higher levels of glazing, the opportunity for risk free shutoffs may be marginally shorter. This would be particularly evident in extremely cold climates where the risk of dropping below the set point would be higher, similar to Figure 38, but in a more extreme manner. The equivalent impact on risk may also be observed in hotter climates, illustrated in Figure 39, as the internal temperatures would likely approach the upper limits more quickly than demonstrated in the case study building. When we consider the building response in Figures 38 and 39, once the active temperature control is removed at 18:00, we observe a maximum difference in $T_z$ of 0.38°C and 1.29°C between different models respectively. When we only consider reasonable glazing/opaque area ratios in line with both existing industrial office buildings and building regulations these differences are 0.13°C for Figure 38 and 0.88°C for Figure 39. This would suggest that the sensitivity of results to building thermal properties is low supporting the portability of the study to other building fabric configurations. In conclusion, this sensitivity analysis demonstrates that varying levels of glazing will influence the buildings internal air temperature. However, the impact during the AHU operating hours, which are the core focus of this study, is very low to negligible. Furthermore, the impacts outside of the operating hours suggest the findings are reasonably applicable to other scenarios and increase the generalizable nature of the study. As shown in Figures 38 and 39 the internal air temperature is quickly returned to its controlled state in each case, meaning no additional risk or impact on the occupants would be incurred.
4.2.7 Step 6 - Final Implementation

The final element of the framework, Step 6, captures each of the outputs, final decision on risk and implementation of the overall project preparing the site for commitment to participate in the applicable DR programme and DS3 system services. Based on the asset selection, categorisation and risk assessment process completed on this case study site, illustrated in Figure 40, it was found that the six assets classified as Level 1 would be suitable for DR and electricity market participation, allowing the final decision on their participation to be made with confidence. Of these assets, the five AHUs, including the AHU selected for additional modelling risk assessment, and one CHP unit, if selected, located in the same building have the potential to form a useful flexible capacity as individual participating units or as an aggregated response portfolio. On this representative case study site, scaling the combined capacity of the suitable AHUs from the 15 kW unit selected for further analysis, there is clear low-risk potential for up to 75 kW of flexible capacity from just the AHUs in this one building. Accounting for exceptional circumstances or potentially reduced participation of certain AHUs, it is realistic to expect that between 35 kW to 75 kW of flexible capacity would be consistently available from this evaluated site to contribute to DR schemes. Based on the evaluation of this representative case study building, this range of flexible capacity provides an insight into the potential available throughout the wider industrial sector and offers a general depiction of what can realistically be expected from comparable sites and similar buildings in this area.
4.3 Discussion

A number of insights and valuable learnings were achieved through the implementation and practical application of this framework on the case study industrial site. Generally, this implementation demonstrates the advancement of this research area, as without the structured framework it would not have been possible to identify the suitable industrial assets on the case study site for DR participation. This helps to overcome the unknowns and previous lack of understanding that were barriers to the engagement and effective adoption of this concept. Another advantage of this framework is the prioritisation of stakeholder engagement throughout the process, which stemmed from the particular emphasis placed on this aspect by the ISO standards. The influence of existing industry best practices and alignment with SOPs also ensure the stakeholders involved are prepared to consume the information and processes as they are tailored to the setting and format that they are accustomed to working with. This engagement with all relevant stakeholders provides a comprehensive pool of knowledge and varied perspectives for all of the aspects considered, offering valuable discussion points and experience from SMEs that direct the success and sustainability of the project. Furthermore, Step 4 and the application of the developed risk-assessment modelling tool in Step 5 facilitated
the risk-assessment of suitable assets, which previously would not have been possible. This new analysis provided by the framework assisted the illustration and mitigation of identified risks, which further reduced the perceived risk of participation that was previously another barrier to industrial engagement in national DR programmes. The flexible capacity contribution from low-risk assets on this case study site provide a clear demonstration of the potential available on any other industrial site. Therefore, the added benefit of this implementation is that it can help to encourage additional industrial participation in DR and increase this sector’s contribution to the overall levels of flexible capacity required to maintain the national electricity grid.

The overall outcome of this final implementation demonstrates there are numerous assets on an industrial site that have potential to provide flexible capacity contributions to participate in national DR programmes. Depending on the site, the number of Level 1 assets can vary but also the potential to move assets through the levels, particularly from Level 2 and 3 to Level 1, which has a significant impact on the capacity figures achievable on a single site. On less risk averse sites, industries with considerably more ancillary services or sites with more capital available to tailor their processes or site-layout to target these services, additional assets can be included within the Level 1 category. The assets identified on the case study site were the most suitable and lowest risk assets available and demonstrate the very minimum and most realistic example of flexible capacities available from a highly risk averse industrial site. This does however highlight the considerable opportunities for this concept, as these specific assets would commonly be found on most industrial sites in this sector. In the Irish context for example, many similar examples would be present across the LIEN and through additional uptake of this concept would have an impact on the national scale. The capacities achievable are likely to benefit the participants and wider national electricity grid considerably if these base levels of flexible capacity can be safely achieved across the industrial sector. Furthermore, the actual capacities achievable across the industrial sector using this framework are likely even larger as other common utility assets previously discussed could potentially be included on different sites to create larger and even more useful flexible capacity aggregations.

Another outcome from the case study implementation of this framework is that the SMEs and stakeholders approached on industrial sites tend to be more risk-averse the closer an asset or its function gets to production or the value adding aspect of the sites operations. The inclusion of entire AHU capacities or varying fan speeds and even other assets like compressors or chillers previously discussed are more acceptable in this sector. Whereas the inclusion of a
production asset’s standby energy consumption outside of production hours or cleanline water bath heater, which is not directly production related, would not even be considered. While these examples would not have comparable capacities, and would not have been suitable for DR participation compared to the assets eventually selected, they do allude to an element of subjectivity in the risk-assessment and ranking process. Although having representatives from each of the previously outlined teams and conducting the engagement and ranking processes through semi-structured and silent brainstorming sessions including the affinity diagram process for unbiased responses, the human element of the process is still a potential limiting factor. This may be reduced through further successful implementations and case study examples similarly to the perceived risk of overall industrial participation in DR; however, it is less likely in the short-term future of this concept. Moreover, while most of the SMEs on industrial sites will have completed similar training programmes and gained comparable experience dealing with these assets, the universal subjectivity of assigning categorisation levels during this process may need further work. Through additional implementations of this framework and as asset portfolios for DR on varying sites are built up, an element of standardisation may be achieved. From this level of acceptable low-risk participating assets, sites can begin to introduce other assets initially categorised in the higher levels to participate, particularly as the need for this flexible capacity on the grid increases and providing these capacities offers the participant larger benefits and more lucrative incentive payments.

The underlying concept of this study and main intention of the results it will produce is to advance the industrial sectors participation in DR and develop the current body of knowledge by building upon existing research and strengthening comparable bodies of work. The intention and its application align with the fundamental belief that there is flexible capacity available from buildings in different sectors to participate safely in DR schemes. One similar study focused on an optimal price-based control strategy of HVAC systems in a multi-zone office space [149]. While this study only considers a single use commercial office building, purpose built for this main function it does offer valuable comparison. In this case, comparable DR capabilities were demonstrated through a similar modelling approach that also resulted in minimal impact on thermal comfort, particularly in the lower comfort thresholds. The reduced order modelling approach presented in this thesis is also suitable for coupling with extraneous applications, thereby offering the potential to integrate risk of DR participation for AHU systems into broader decision-support systems. The presented framework is both highly scalable, transferrable and the model functionality can be extended to include additional
4. Implementation

Parameterization. Further similarities can also be drawn to a study investigating the quantification of electricity flexibility in another designated office building for DR [150]. This particular study also focuses on a large commercial building, which is not directly relatable to the industrial buildings considered and the focus of this research. However, the results of that study also demonstrate the evaluation of the considerable flexible capacities available for DR through a similar approach. Their evaluation also incorporates the influence of occupants’ behaviour and thermal comfort preferences, which highlights the additional capabilities and risk mitigation achievable under less stringent temperature limits. These comparable examples, while not focused on the industrial sector, demonstrate elements of the potential achievable and the value of carefully considered modelling approaches; however, they do not focus on the financial performance and additional benefits achievable through this concept. This further value, outlined in Chapter 5 of this thesis, is also vital to demonstrate the true benefits of participation and is key to encouraging additional engagement from the industrial sector. This demonstration helps to build the platform upon which the research presented in this thesis sits and offers a solid foundation to advance and grow the knowledge in this area for the benefit of new industrial participants in DR programmes and the wider national electricity grids.

An important aspect of the modelling approach for the risk-assessment modelling tool was to ensure the transferability and general applicability for its purpose in the industrial sector. To provide the most value, the concept had to be scalable and suitable for numerous applications in this industry. The main benefit of this is its modular design and simple input structure, allowing the user to evaluate any internal space regardless of size, location or occupancy, as these aspects just need to be captured during the initialisation phase. This allows the user to apply the risk-assessment modelling tool to any relevant internal space served by an AHU on their site, to assess the operational risks of including that particular asset during the initial framework application or later at any stage. For example, if another AHU initially categorised at a higher level undergoes system changes or physical alterations that allow it to be progressed through the levels and be considered for DR participation. Moreover, once the model has been setup and applied to a specific zone, numerous evaluations can be completed allowing the user to assess the impact of different shutoff durations and varying temperature setpoints and limits. The main value add in this area is that any of the potential DR system services can be targeted, from quick response, short duration events to slower response longer duration shutoffs and even capturing each of the categories by responding and remaining off for the entire duration required. This allows the user to quantify the potential risk levels for each response category,
even incorporating pre-cooling or pre-heating of the zone although this is less financially rewarding, to consider their potential response portfolio based on virtual evaluations before committing to their DR participation. Finally, the model enables participants to adjust the internal temperature setpoint and limits, allowing them to evaluate and illustrate the impact of adjusting these variables on risk levels. This particular feature can clearly demonstrate the potential benefits achievable and reduction in risk levels of marginally modifying the temperature setpoints on the overall DR potential of these internal spaces.

An important aspect to consider about the framework and modelling presented in this thesis is that the research is focused on industrial sites and electricity market participation. It is therefore important to highlight that the included decisions, assumptions and future results should be understood in the context of this sector, these particular buildings and the purpose being studied. A potential limitation of the modelling approach is that internal air temperature is the main indicator of performance and is used to highlight any potential risks. This indicator was selected as it is commonly available through an industrial site’s BMS and is generally used as part of their control strategies. It was therefore chosen as the most common gauge of thermal comfort in practice, over CO₂ levels or humidity, which are used to calculate indoor air quality, to maximise the suitability and applicability of this approach on industrial sites and avoid specialised infrastructure or bespoke solutions. This work also focuses on suitability for the short, fast responses of DR where temperature changes in these building types most clearly illustrated the effect and any possible risks. The shutoff durations and expected frequency of annual DR events, likely less than one a month, ensured the risk of mould growth in the zone increasing through participation was minimal. The potential for CO₂ levels within the zone to exceed acceptable limits, approximately 1,000 ppm according to ISO/TR 17772-2 [244] during a shutoff were also low-risk based on the zone size and occupancy levels. A study assessing the impact of shutting off the CAV mechanical ventilation to an occupied space, similar to the case study system, demonstrated that there is low-risk of CO₂ levels exceeding acceptable limits for durations comparable to DR events. In this study, the CO₂ concentration of a 129 m³ room occupied by 25 people was assessed, finding that it took over 35 minutes for the CO₂ levels to rise from 700 ppm to 1,200 ppm, defined as unacceptable by ISO/TR 17772-2 in this case [245]. The occupant density of this space is much higher than that of the case study office space, with approximately 125 to 150 occupants expected in the 2838 m³ zone. This further mitigates the risk of CO₂ levels spiking unacceptably in the periods expected during a DR event. Additionally, these industrial office spaces fall within bracket 1 of the ventilation intensity
requirements defined in ASHRAE 62.1 [246], meaning they are only required to meet between 0 and 1.0 L/s/m\(^2\) compared to 2.0 to 3.0 L/s/m\(^2\) for bracket 3, which the classroom in this study would fall into [245], further minimising potential CO\(_2\) concentration risks. Finally, measured CO\(_2\) levels within the occupied industrial office space, illustrated in Appendix A Figure A5, averaged approximately 450 ppm and only hit a maximum of 540 ppm during a 3-week period in July while the AHU was in operation. This further demonstrates the low-risk of CO\(_2\) levels peaking from this baseline to unacceptable levels, compared to the similar study, during a shutoff of the duration expected from a DR event. Although including additional inputs like humidity or CO\(_2\) may improve the calculation of overall indoor air quality in the space, this would negatively affect the computational efficiency and complexity of the model. In situations where participants only have minimal sensors or connectivity, it would also push the model away from its generally applicable and transferrable approach, as temperature sensors were found to be the most common data source on the case study site. Although fresh air percentage is included in the modelling analysis, the internal zone CO\(_2\) levels and rate at which these increase during a shutoff and decrease thereafter are not currently considered. This may be seen as a limitation following the emphasis of COVID-19 restrictions and their impact on certain AHU operations. However, due to the modularity of the modelling approach and software this could be included if necessary. In this case, CO\(_2\) sensors could be installed within the room to gather the required data. This would allow simple warnings to be created if the CO\(_2\) ppm were increasing too rapidly or getting close to exceeding the upper threshold during a DR shutoff. The risk assessment procedure could then be updated to include this aspect, supplementing the information generated by the risk assessment process and allowing the opportunity to set up limits on the allowable shutoff durations based on CO\(_2\) concentration in addition to temperature thresholds and drift limits.

### 4.4 Conclusions

The primary intention of this chapter and the fundamental goal of this research is to grow the body of knowledge, reduce the perceived risk and level of uncertainty surrounding engagement in DR programmes and outline the potential benefits, like financial performance and emissions reduction, to advance the industrial sector’s participation and encourage additional engagement in these schemes. Elements of this aim were achieved through demonstrating the proposed framework and risk-assessment modelling tool on a representative industrial case study site in this chapter. Furthermore, confirming the building being analysed was suitably characterised
using appropriate standards to capture its inherent physical properties and ensuring the model was calibrated and validated with carefully collected empirical data was important to maintain the rigour of this presented framework. The calibration process resulted in a modelling tool capable of predicting internal air temperatures to an acceptable level of accuracy, highlighted by the final statistical metrics, achieving an RMSE of 0.3°C, an R² of close to 0.5, a total of 0.2°C MAE, only 0.22% MBE and a final PC of 0.93. Moreover, a sensitivity analysis was conducted, focusing on the UA-values and solar gains, to fully outline their impacts and present a deeper understanding of the models outputs. This analysis of the influence of extreme conditions suggests that the sensitivity of results to building thermal properties is low, supporting the portability of this modelling tool and its suitability throughout the industrial sector.

The potential capacities achievable, as demonstrated through the implementation of this framework offer a number of useful and increasingly valuable benefits to the national electricity grid. The 35 kW to 75 kW capacity expectation may vary based on different site processes and configurations; however, it provides a clear indication and representative range of participation capabilities across the numerous and diverse sites in the industrial sector. Allowing participants with significantly higher or lower suitable capacities to be captured within one grouped figure that represents the impact potential of this sector. These potential flexible capacity figures can also be scaled up to demonstrate a variety of different scenarios and illustrate their varying levels of impact. The historical and future extreme weather conditions and an example of a hotter climate, Budapest in 2050, representative of another European climate detailed in this chapter, present further opportunities for additional risk assessment and evaluation. These examples and additional analysis will be presented in Chapter 5, to develop the area of risk assessment of AHUs in the industrial sector further and highlight the potential impact of increased participation in national DR programmes. This will help to reduce the perceived risk associated with this concept and build the body of knowledge in this research area. Additional illustration of the benefits achievable, including financial performance, emissions reductions and even dual benefits, based on the outcomes of implementing this framework, will assist the encouragement and further uptake of DR in the industrial sector and help to provide the required flexible capacities to the TSOs and wider national electricity grids.
Chapter 5

Results, Impact & Discussion

5.1 Introduction

This chapter, shown in Figure 41, outlines the modelling assessment and results of utilising the risk-assessment modelling tool, during Step 5 of the framework, to evaluate potential operational risks outlined in the previous chapter. The evaluation of actual grid events, typical boundary conditions and other relevant influences are analysed to provide a demonstration of feasible scenarios. The aim of this illustration is to outline possible risks, potential mitigation strategies if applicable and demonstrate to potential participants the low risk of including the identified assets in DR programmes, particularly in the context of the specific response timeframes. The potential benefits achievable through including identified industrial assets in national DR programmes are illustrated, to encourage additional uptake and proliferation of DR participation in the industrial sector. The potential impact of increased DR adoption on the wider electrical grid is quantified to highlight the possible benefits to the national grid, which was previously identified as a driver for this research. Additionally, the potential financial benefits achievable for the individual participant, also highlighted as a driving factor, are presented to capture the full impact and value of increased DR participation in the industrial sector. Through each of these evaluations and their resulting discussions, the intention is to reduce the level of perceived risk and unknowns around the topic of industrial DR and encourage additional engagement from this sector to the benefit of all pertinent stakeholders.

Figure 41. Overview of thesis, highlighting the current chapter and research objectives to be addressed.
5. Results, Impact & Discussion

5.1.1 Background
The overall framework and risk-assessment modelling tool, presented in Chapter 3 and Chapter 4, highlight how to assess and identify industrial assets for DR participation and in the case of AHUs how to model and further assess any operational risk associated with their participation. This research advances the existing knowledge in this area, as detailed implementations of industrial DR frameworks and a specific industrial AHU risk-assessment modelling tool did not previously exist in the literature, as outlined in Chapter 2. One of the benefits of these novel contributions are the new opportunities to detail and quantify the impact of advancements in the area of industrial DR effectively, as detailed in this chapter. The clear value of this implementation and additional discussion of industrial DR capabilities is the reduction of one of the main barriers to its success, the unknown impacts and perceived risk associated with participation. Through the quantification and illustration of the actual operational risks on a representative case study site participating in DR events shown in this chapter, the perceived risk can be reduced, minimising this barrier and allowing other sites to introduce mitigation measures if needed to further improve the confidence in their performance. Additionally, the demonstration and further discussion of the actual potential risks and performance capabilities of a representative industrial site participating can help to encourage further participation from this sector. Allowing new participants to achieve the demonstrated benefits of participating in national DR programmes, while also increasing the levels of flexible capacity available to the grid from a sector that has considerable potential.

5.1.2 Research Objectives
A core aspect of this thesis and of each of the ROs highlighted is the demonstration of insights to encourage additional industrial participation in DR. Through identification of the relevant benefits, barriers and driving factors (RO1), the presentation of a systematic asset selection and categorisation framework (RO2) and development of a suitable risk-assessment modelling tool (RO3) it was possible to identify the available potential. The final aspect to encourage further industrial participation in DR is to detail potential operational risks and quantify the achievable benefits, highlighting their impact for the industrial participant and wider national grid. This aim is captured within RO4, presenting discussion around the actual operational risk of selected AHUs, identified as low risk, participating in DR programmes presented in this chapter. Furthermore, the potential benefit and influence on electricity grid at a local, regional and national scale are presented, offering new insights into the actual impact of increased industrial participation in DR. The financial aspect for the individual participant is also explored to
highlight the impact and potential influence this may have on their operations and to encourage further engagement from the industrial sector through this representative demonstration.

**RO4.** Quantify and highlight the potential benefits of selected industrial assets deemed as low risk being incorporated into DR programmes and illustrate their potential impact on the Irish national electricity grid.

### 5.2 Modelling

The aim of this section, in line with RO3 and as an example of the modelling evaluations from Step 5 of the framework, is to evaluate any potential operational risks associated with a suitable industrial asset participating in DR, which will help to minimise the perceived risk based on these demonstrations. The value of this evaluation is that it is then possible to quantify and evaluate the potential benefits of the selected asset, deemed as low risk, being incorporated in DR programmes to illustrate their potential impact as captured in RO4. Following the implementation of the proposed framework, it was determined that selected AHUs, in this case serving industrial office spaces, were low-risk assets suitable for DR participation, highlighted in Section 4.2.4 Table 12 and Figure 32. The risk-assessment modelling tool described in Chapter 3 and Chapter 4, evaluates any operational risks to assess the performance and its impact potential. The predominant indicator of risk levels during an AHU shutoff for DR events will be viewed as the internal air temperature deviating from defined temperature thresholds and the ASHRAE limits for acceptable temperature drift, outlined in Section 2.3.2.5.

#### 5.2.1 General Risk Assessment Scenarios

The aim of this section is to assess any risk to indoor thermal environments and evaluate the suitability of industrial office spaces providing AHU capacity to the national electricity grid for DR. The predominant indicator of the perceived risk to occupant comfort in the area being assessed is the internal air temperature and its rate of change during the times in question. The ASHRAE Standard 55 offers considerable insights into this domain with defined temperature ranges and limits of acceptability necessary for these zones. Table 5.3.5.3 of this standard, shown in Section 2.3.2.5, outlines the maximum operative temperature changes allowed over specified time horizons with a few additional acceptability requirements. The conditions set out in this document form the basis of the risk factors and acceptable limits for the results of this study. Any temperature drift or ramp of more than 2.2°C in a one-hour period will be categorized as unacceptable and high risk to occupant thermal comfort, Temperature Drift Risk.
1 (TDR1). Furthermore, any temperature drift or ramp greater than 1.1°C in a fifteen-minute time interval within this same one-hour period or at any stage will also be categorised as unacceptable and high risk to occupant thermal comfort [55], (TDR2).

Three thermal comfort thresholds are applied to assess any potential risk to the occupant’s thermal comfort thoroughly, shown in Table 18. The first threshold, Thermal Comfort Risk 1 (TCR1), is based on the case study site’s BMS settings with the lower limit being 20°C and the upper limit being 25°C. These temperature limits are applied on the case study building and additionally are closely aligned to the normal level of expectation outlined in the ISO 7730 standards [56]. TCR2 applies the same lower limit of 20°C but has a marginally tighter upper limit of 23°C. This smaller threshold highlights times where the zone temperature exceeds a reasonably high temperature limit, which could be classified as an overheating event. TCR3 enforces a similarly tight threshold, with a lower limit of 20.5°C and upper limit of 23.5°C. This further threshold captures temperature deviations outside of the reasonable temperature limits, while placing additional emphasis on potential overcooling events. These conditions will be applied during the risk assessment process, where the criteria for a no risk or risk result will be as outlined in Equations (13) and (14). For a scenario to be considered as representing no risk, the internal air temperature must remain within the outlined thermal comfort threshold and cannot exceed either of the temperature drift criteria at any stage of the analysis, as shown in Equation (13). A scenario will be deemed as presenting a risk, if the internal air temperature falls outside of the defined thermal comfort threshold or if it exceeds either of the temperature drift criteria at any stage of the risk assessment, as outlined in Equation (14).

\[
No\ Risk = \begin{cases} 
TCR1: & \text{if } 20.0 < T_Z < 25.0, \text{Max Drift} < \text{TDR1 and Max Drift} < \text{TDR2} \\
TCR2: & \text{if } 20.0 < T_Z < 23.0, \text{Max Drift} < \text{TDR1 and Max Drift} < \text{TDR2} \\
TCR3: & \text{if } 20.5 < T_Z < 23.5, \text{Max Drift} < \text{TDR1 and Max Drift} < \text{TDR2} 
\end{cases} 
\]

\[
Risk = \begin{cases} 
TCR1: & \text{if } T_Z < 20.0, T_Z > 25.0, \text{Max Drift} > \text{TDR1 or Max Drift} > \text{TDR2} \\
TCR2: & \text{if } T_Z < 20.0, T_Z > 23.0, \text{Max Drift} > \text{TDR1 or Max Drift} > \text{TDR2} \\
TCR3: & \text{if } T_Z < 20.5, T_Z > 23.5, \text{Max Drift} > \text{TDR1 or Max Drift} > \text{TDR2} 
\end{cases} 
\]
Table 18. Shutoff times, durations, external temperature files and thermal comfort thresholds used as modelling scenario variables for assessing potential risks.

<table>
<thead>
<tr>
<th>Shutoff Time (hh:mm)</th>
<th>Shutoff Duration (mins)</th>
<th>External Temperature Data Files</th>
<th>Thermal Comfort Threshold (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>07:00</td>
<td>5</td>
<td>Actual 1 2050 H</td>
<td>TCR 1 [20–25]</td>
</tr>
<tr>
<td>09:30</td>
<td>15</td>
<td>Actual 2 2050 C</td>
<td>TCR 2 [20–23]</td>
</tr>
<tr>
<td>11:00</td>
<td>30</td>
<td>Actual 3 2100 H</td>
<td>TCR 3 [20.5–23.5]</td>
</tr>
<tr>
<td>14:00</td>
<td>60</td>
<td>Past H 2100 C</td>
<td></td>
</tr>
<tr>
<td>15:30</td>
<td>Past C 2050 BP H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17:00</td>
<td>2030 H 2050 BP C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The AHU shutoff times and durations for the scenarios, Table 18, were selected following a study of actual GFEs and aggregator information, to ensure the study was fully aligned with real world grid interactions. From analysis of the EirGrid grid frequency data [21], it was possible to identify when the frequency approached or dropped below 49.7 Hz, which generally indicates a GFE and the need for a response. By contacting the EirGrid information and data archives department directly, it was possible to gather the actual grid frequency data, in zip files, for the years 2019 and 2020. Using Python to process the raw data, allowed the large volumes of data to be extracted from the zip files using a specific Pandas code within Jupyter Notebooks to read them within this software. Writing the code in Pandas simplified the process of reading each monthly dataset, as they were provided in various formats including .txt, .xlsx, .csv and .tsv, into one common data-frame for analysis. Further processing was required to align each of the one-second timestamps and rename each of the values appropriately according to the overall naming convention. Once the final, common data-frame for each of the years was created, the files were prepared for further analysis. Utilising Python again to analyse the processed data allowed the findings to be drawn and the outputs in Appendix A, Table A1, Figure A3 and Figure A4 to be presented. This helped to demonstrate when the national grid frequency dropped below 49.7 Hz, indicative of a GFE, and when it dropped below 49.75 Hz, which may not always result in a GFE or DS3 response but does illustrates times at which the grid was under considerable strain. The events occurring during the AHUs operating schedule were quite evenly spread throughout the day from early morning to late afternoon. Based on this evaluation, the six-shutoff times shown in Table 18 were selected to accurately represent and analyse potential shutoffs as part of this research.

The shutoff durations were also selected to align with the DS3 system services, particularly the reserve and fast-acting categories [24], most suitable to DR participants in the Irish electricity market. These DS3 system services would be the categories a prosumer would offer in response.
to a GFE. Therefore, if no risk could be proven during these timeframes then an overall conclusion on the DR potential could be drawn. The five-minute duration is the most closely aligned to the quick response and short duration grid events, which are the most valuable to the grid and lucrative to the responder. With EirGrid offering €2.16 and €3.24 per MWh for fast frequency response and primary operating reserve respectively, which are required for between 2 and 15 second responses [25]. These are compared to €1.24 per MWh for tertiary operating reserve 2, which is required within 5 minutes for a 20-minute response and is the slowest of the frequency response DS3 system services. The longer durations shown in Table 1 were then selected to evaluate the potential to shut off and remain off for longer amounts of time, thereby allowing the responder to maximise their payments by capturing the fast response incentives and remaining off to avail of the remaining payment categories. The results of this evaluation can also help to illustrate the potential of participating in the slower response but longer duration events, for participants where fast responses are not feasible. These categories are also required by the grid and help to create additional capacity and flexibility in the overall DR portfolio.

5.2.2 General Risk Assessment Results

To provide an evaluation of potential operational risks to the case study site participating in DR events, the risk-assessment modelling tool was utilised during Step 5 of the overall framework. The variables outlined in the previous section and shown in Table 18 were used to evaluate any risk during this assessment. A permutation was created for each shutoff time, shutoff duration and external temperature weather file, including actual measured external temperature profiles, past and future hottest and coldest days and these predicted values for Budapest, as a representative example of another European climate. Each of these scenarios were assessed under each of the thermal comfort thresholds, resulting in 936 individual risk-evaluation scenarios under each of these specific conditions. These scenarios, simulated with the risk-assessment modelling tool, allowed the assessment of any possible risks encountered if the selected industrial AHU were to respond to the DR event in each case. The results of each of these scenarios are illustrated in Figure 42, where the resulting outcome is categorised by colour, with green representing no risk, red an overheating risk and blue an overcooling risk.
5. Results, Impact & Discussion

As illustrated, none of the scenarios for actual measured days encountered any risk under TCR1 criteria. This is only a brief snapshot of three test days, however as these actual days were measured during June 2020, where overheating may have been a concern and so offer a positive indication that these assets can be included in DR programmes under normal conditions at very low levels of risk. During the scenarios of more extreme weather simulations, there were no risks encountered for the case study site, excluding Budapest data, for 5, 15 and 30-minute shutoffs under the TCR1 criteria. For the longer events evaluated on the case study site, the potential overheating events identified as a risk were only triggered and deemed a risk under the TDR1 condition. The only exceptions to this were the possible events occurring during the

<table>
<thead>
<tr>
<th>Time</th>
<th>07:00</th>
<th>09:30</th>
<th>11:00</th>
<th>14:00</th>
<th>15:30</th>
<th>17:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration [min]</td>
<td>5 15 30 60</td>
<td>5 15 30 60</td>
<td>5 15 30 60</td>
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<td>Actual 1</td>
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<tr>
<td>Actual 2</td>
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<td>Past H</td>
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<td>Past C</td>
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<td>2030 C</td>
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<td>2050 C</td>
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<td>2100 H</td>
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<td>2050 BP H</td>
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<td>2050 BP C</td>
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Figure 42. Overview of each of the general risk assessment scenarios categorised by no risk (green), overheating risk (red) and overcooling risk (blue).
2050 BP H example, representing the hottest predicted daily temperature profile in Budapest under the most pessimistic carbon predictions, which also exceeded the upper temperature limit of TCR1 in eight cases where the shutoff was less than one hour. For the scenarios run under TCR2 and TCR3 criteria shown in Figure 42, each of the events classified as risks were triggered by excursions outside of the temperature threshold limits, while 21 of these events deemed a risk also exceeded the requirements of TDR1. Between these two risk criteria, TCR2 registered more overheating events than TCR3 as a number of the marginal days just exceeded the 23°C but did not go outside the 23.5°C upper limit of TCR3.

The AHU being analysed was unable to meet the minimum temperature requirements of any of the TCR categories, therefore encountering an overcooling risk, during 2050 BP C, the extremely cold predicted coldest day in Budapest 2050. Similarly, it also failed to meet the minimum required 20.5°C of TCR3 during the Past C day, which is the coldest day on record for the case study location. This could be corrected in practice by increasing the actual heating coil capacity although this would incur an additional capital and energy cost, which would be detrimental to the project intentions and actually be directly classified as one of the barriers previously identified. None of the overcooling risk events exceeded TDR1, while none of the events across any of the simulated scenarios exceeded TDR2 at any stage throughout the evaluation. There were no risk events recorded during the five-minute shutoffs in the TCR2 category or the five or fifteen-minute shutoffs in the TCR3 category aside from the Past C day, the coldest day on record for the case study site location. The performance and risk levels over all of the coldest days shown in Figure 42, with the exception of Past C under TCR3 criteria again, demonstrate very promising potential for this concept in the Irish context. The Irish electricity grid is particularly influenced by wind generation, whose capacities are growing every year, so the clear risk free flexible capacities available from this concept during these winter times could be invaluable to the Irish TSOs. This concept could have a considerable impact during the cold and windy winter months, where the volatile wind resources are often subject to more severe fluctuations, complimenting the TSOs ability to maintain reliable control of the national electricity grid.

The temperature drift that occurred for each shutoff duration across all of the scenarios is illustrated in Figure 43. This confirms and clearly demonstrates the expected result that the longer the shutoff period is the larger and more variable the resultant temperature drift will be. This is demonstrated numerically by a mean drift across all of the general risk assessment scenarios of only 0.2°C, minimum of 0°C and maximum of 0.3°C for each of the five-minute
shutoff durations. In contrast, the sixty-minute shutoff durations resulted in a mean drift value of 1.6°C, a minimum of -0.3°C and maximum drift of 3°C in the most extreme scenario. This general outcome reinforces the suitability and suggested potential of industrial AHUs participating in DR, as the more valuable and lucrative DR system services are focused on the quick and short response categories where these industrial assets show the lowest levels of risk.

![Temperature Drift vs Shutoff Duration](image)

*Figure 43. Box and whisker plot of internal air temperature drift for each of the shutoff durations considered for all general risk assessment scenarios, with the median represented by a green horizontal line.*

The temperature drift occurring during each shutoff time for all of the scenarios is illustrated in Figure 44. The most significant outcome from this study represented in this figure is that the temperature generally drifts in a positive direction when the AHU is turned off and therefore there is more of a risk of overheating than overcooling on this case study site. This is demonstrated by each of the median lines falling at approximately the 0.5°C mark. This figure also illustrates that generally the highest temperature drifts occur later in the day, particularly during the 14:00 and 15:30 shutoff times. These two times, in addition to the 11:00 shutoff time, are also the least likely to incur overcooling risks, as they did not result in negative drift at any stage during the scenario analysis. The earliest shutoff time assessed, 07:00, represents the lowest risk of overheating, with the lowest median indoor air temperature drift. This category is also the only shutoff time analysed not to exceed a 2°C temperature drift at any stage, highlighting it as a particularly low-risk shutoff time.
The actual indoor air temperature for each of the hottest and coldest days analysed is presented in Figure 45, illustrating the median temperature within the zone in addition to the hottest and coldest extreme temperatures for each of the scenarios. In the case of the Irish weather data, the past data represents the most volatile and extreme conditions, while the future scenarios gradually increase in temperature drift and variability from closest to furthest away in time. Although even in these extreme cases, the temperature within the zone never rises above 24.9°C or drops below 20.5°C at any stage. These values also highlight the influence of thermal tolerance and the temperatures expected by the occupants of office spaces participating in DR events. Thermal tolerance, which is the state of mind of occupants expressing their total unacceptability to the thermal environment after physiological and psychological regulation and any behavioural adjustments are accounted for [247]. In a study assessing a range of people from young, middle aged and older it was found that the tolerance levels of temperature were actually much higher than allowable limits, in his case reaching over 26°C before beginning to be deemed unacceptable [247]. Therefore, none of the scenarios analysed that remained within the drift limits would have been considered a risk in relation to tolerance levels on the case study site. The age groups assessed in this study are generally representative of the occupants expected in industrial office spaces, therefore further emphasising the low-risk of complaints and unacceptable conditions caused by AHUs participating in DR events. This is further demonstrated by the actual temperatures deemed thermally unacceptable by the majority of
occupants assessed being over 2°C hotter than the highest internal air temperature reached during a DR shutoff in the extreme cases analysed. Additionally, thermal expectation plays a role in the actual tolerance levels of people in occupied spaces. This is further demonstrated in practice, where occupants adapt their behaviour and expectations based on the temperature during hotter and colder months [248]. In reality, people adjust their clothing, behaviours like consumption of hot or cold beverages, and activity levels to the temperature, therefore changing their tolerance levels and the temperatures that would be deemed unacceptable. In another study, this is demonstrated further with the majority of occupants not classifying temperatures in excess of 24.5°C and higher as warmer than expected or unacceptable [248]. This further reduces the potential risk of incurring unacceptable conditions for the occupants of office spaces where the AHU serving the space is participating in a DR programme.

The colder scenarios also provide a general indication of the possible impacts of climate change and the potentially hotter temperatures anticipated in Ireland in the future. There is a noticeable increase in the lowest temperatures expected compared to the historical coldest day, with the coldest day in 2100, 2100°C in Figure 45, most clearly illustrating this gradual increase compared to its equivalent day in 2030. The Budapest scenarios illustrate a much more volatile and wider range of temperatures, which add greater variability to the internal temperature of the zone with a recorded upper extreme temperature of 27.2°C and mean of 24.3°C during the hottest day and a lower extreme temperature of 19.4°C and mean of 20.3°C during the coldest day assessed. There is clearly much higher risk of participation in DR schemes in this climate compared to that of the case study site without appropriate changes to the AHU capacity or building specifications. This demonstrates the transferability and applicability of the modelling.
assessment tool, however in practice operational changes or physical alternations would be required to achieve similar low-risk of participation with the same building characteristics in this more extreme European climate.

The daily temperature profile for each Actual Day 1 scenario analysed under TCR2 conditions is presented in Figure 46. The normal AHU operating schedule runs from 06:00 to 18:00 as discussed and outlined by the temperature remaining comfortably within the limits during this period aside from the simulated temperature peaks during shutoff analysis. Each of the peaks for the individual scenarios are also illustrated as part of the evaluation. The four failing events on this day, under TCR2 conditions, are demonstrated by the temperature spikes highlighted in Figure 46. These simulated shutoffs caused the internal air temperature within the zone to exceed the upper temperature threshold of 23°C, therefore they would be considered risk events under these conditions. Each of these risk events were encountered during one-hour long shutoff scenarios, which were the longest expected grid events assessed. As illustrated, none of the other scenarios analysed exceeded the temperature or drift limits, which further demonstrates the low-risk capabilities these assets possess for DR participation. This figure also highlights that none of the scenarios would have exceeded the temperature limits of the case study building, TCR1, at any stage and therefore would be considered risk-free for participation in DR schemes throughout this day of actual measured data.

![Figure 46. Daily internal air temperature profile and temperature set point (green dashed line) for each scenario analysed for actual Day 1 data under TCR2 conditions, illustrated by the red dashed lines and annotations.](image)
5.2.3 Actual Grid Event Risk Assessment Scenarios

To gain further knowledge and a deeper understanding of the impact and perceived risk of practical DR participation, it was important to investigate actual GFEs that had previously taken place and their associated real world conditions. An aspect of this additional investigation was the collection of the actual grid frequency data from EirGrid [21] for the two years prior to this study, 2019 and 2020, as discussed in Section 5.2.1 and highlighted in Appendix A, Table A1. By examining this actual Irish national grid frequency data, it was possible to identify previous times that the grid frequency dropped below 49.7 Hz, which signifies a GFE and would represent an opportunity for DS3 system services to be called upon. By extracting the critical aspects of this data, it was possible to isolate when these previous events had occurred and isolate occasions when the AHU would have normally been operating. These days and start times are detailed in Table 19, illustrating the vital information related to each GFE. The external air temperature data from the case study site’s BMS, available at 15-minute intervals, was also collected for the days on which the previous GFEs had occurred, with the corresponding daily min, mean and max temperatures recorded.

The daily external air temperature profile for each of these days are also illustrated in Figure 47, highlighting a considerable range of temperatures across the years analysed. The temperatures recorded on 3 March 2019 present an example of a particularly cold day, when the AHU would likely be operating in its heating mode to maintain a comfortable internal air

Table 19. Overview of GFEs occurring in 2019 and 2020 during the AHU operating hours and the external temperature collected from the case study site during the same days.

<table>
<thead>
<tr>
<th>Date</th>
<th>Start Time</th>
<th>Duration</th>
<th>Trigger Frequency</th>
<th>Frequency Range</th>
<th>T_MIN Time</th>
<th>T_MEAN Time</th>
<th>T_MAX Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(dd/mmm/yy)(hh:mm:ss)</td>
<td>(s)</td>
<td>(Hz)</td>
<td>(Hz)</td>
<td>(°C) (hh:mm)</td>
<td>(°C)</td>
<td>(°C) (hh:mm)</td>
</tr>
<tr>
<td>03/Mar/19</td>
<td>06:12:59</td>
<td>111</td>
<td>49.703</td>
<td>49.662 – 49.749</td>
<td>4.1</td>
<td>02:45</td>
<td>7.8</td>
</tr>
<tr>
<td>20/Mar/19</td>
<td>16:46:16</td>
<td>4</td>
<td>49.672</td>
<td>49.574 – 49.706</td>
<td>4.6</td>
<td>01:30</td>
<td>11.3</td>
</tr>
<tr>
<td>24/Apr/19</td>
<td>15:21:07</td>
<td>5</td>
<td>49.702</td>
<td>49.608 – 49.711</td>
<td>10.2</td>
<td>03:15</td>
<td>13.6</td>
</tr>
<tr>
<td>08/May/19</td>
<td>09:14:23</td>
<td>7</td>
<td>49.655</td>
<td>49.576 – 49.721</td>
<td>6.9</td>
<td>04:30</td>
<td>10.3</td>
</tr>
<tr>
<td>20/May/19</td>
<td>14:54:12</td>
<td>226</td>
<td>49.743</td>
<td>49.542 – 49.749</td>
<td>8.3</td>
<td>23:45</td>
<td>13.2</td>
</tr>
<tr>
<td>11/Jul/19</td>
<td>07:53:37</td>
<td>5</td>
<td>49.696</td>
<td>49.632 – 49.743</td>
<td>12.5</td>
<td>01:00</td>
<td>16.5</td>
</tr>
<tr>
<td>19/Jul/20</td>
<td>06:26:35</td>
<td>45</td>
<td>49.599</td>
<td>49.599 – 49.748</td>
<td>6.6</td>
<td>23:45</td>
<td>16.8</td>
</tr>
<tr>
<td>23/Sep/20</td>
<td>11:02:15</td>
<td>5</td>
<td>49.531</td>
<td>49.531 – 49.531</td>
<td>9.5</td>
<td>23:45</td>
<td>13.2</td>
</tr>
</tbody>
</table>
temperature within the zone. The 19 July 2020 daily profile offers a contrasting example with a much higher average external air temperature recorded and especially high values in the later hours of this summer day. Each of these examples offer interesting potential risks to the indoor thermal environments served by this AHU if it were participating in DR, warranting further detailed investigation.

![External Air Temperature Daily Profiles](image)

*Figure 47. Overview of external air temperature daily profiles from the sites BMS, for each day on which a GFE occurred.*

To provide a thorough evaluation of any risk to the internal thermal environment of the case study site offering its AHU for DR, each of the previous actual grid event days will be assessed to demonstrate the risk, if any, of their participation. The specifics of each GFE day and evaluation criteria are outlined in Table 20. In this application of the risk-assessment process, a thermal comfort threshold of 20°C to 23°C will be applied in addition to the ASHRAE standards for allowable temperature drifts for human occupancy to evaluate any potential risks of participation. Therefore, under the outlined criteria any deviation outside the 20°C to 23°C temperature range, any drift of more than 2.2°C in a one-hour period or a drift of more than 1.1°C in a standalone 15-minute period or during the same one hour period will result in the response event being flagged as a risk. For this analysis, the risk-assessment modelling tool will be used to simulate the internal air temperature within the zone during the AHUs normal operation on the previous GFE days. This will allow analysis of any impact on the internal zone if the AHU were to shutoff in response, indicative of responding to a DS3 system service signal, at the actual time a previous GFE occurred during those days. To analyse performance...
potential further, for these actual shutoff times the AHU will remain off for a number of other potential shutoff durations in different scenarios, outlined in Table 20. This will assess and demonstrate how long the AHU could remain off without incurring risk to the zone following its response to a DR signal. This will highlight the potential for this asset to provide longer response durations to the grid and possibly benefit from additional incentive multipliers for short- and longer-duration responses.

Table 20. Overview of GFEs occurring in 2019 and 2020 during the AHU operating hours and the external temperature collected from the case study site for the same days.

<table>
<thead>
<tr>
<th>Date</th>
<th>Shutoff Time</th>
<th>Shutoff Duration</th>
<th>Thermal Comfort Threshold</th>
<th>Potential Shutoff Durations</th>
</tr>
</thead>
<tbody>
<tr>
<td>(dd/mm/yy)</td>
<td>(hh:mm:ss)</td>
<td>(s)</td>
<td>(°C)</td>
<td>(mins)</td>
</tr>
<tr>
<td>03/Mar/19</td>
<td>06:12:59</td>
<td>111</td>
<td>20–23</td>
<td>5, 10, 15, 20, 30, 45, 60</td>
</tr>
<tr>
<td>20/Mar/19</td>
<td>16:46:16</td>
<td>4</td>
<td>20–23</td>
<td>5, 10, 15, 20, 30, 45, 60</td>
</tr>
<tr>
<td>24/Apr/19</td>
<td>15:21:07</td>
<td>5</td>
<td>20–23</td>
<td>5, 10, 15, 20, 30, 45, 60</td>
</tr>
<tr>
<td>08/May/19</td>
<td>09:14:23</td>
<td>7</td>
<td>20–23</td>
<td>5, 10, 15, 20, 30, 45, 60</td>
</tr>
<tr>
<td>20/May/19</td>
<td>14:54:12</td>
<td>226</td>
<td>20–23</td>
<td>5, 10, 15, 20, 30, 45, 60</td>
</tr>
<tr>
<td>11/Jul/19</td>
<td>07:53:37</td>
<td>5</td>
<td>20–23</td>
<td>5, 10, 15, 20, 30, 45, 60</td>
</tr>
<tr>
<td>19/Jul/20</td>
<td>06:26:35</td>
<td>45</td>
<td>20–23</td>
<td>5, 10, 15, 20, 30, 45, 60</td>
</tr>
<tr>
<td>23/Sep/20</td>
<td>11:02:15</td>
<td>5</td>
<td>20–23</td>
<td>5, 10, 15, 20, 30, 45, 60</td>
</tr>
</tbody>
</table>

5.2.4 Actual Grid Event Risk Assessment Results

To complement the general risk assessment scenarios and ensure a broader risk assessment, additional analysis was conducted investigating any potential risk to the indoor thermal environment on the case study site if the AHU was to shutoff for previous actual GFEs. Each of the previously occurring GFEs that occurred in 2019 and 2020 were evaluated using this modelling tool. Considering each of the actual GFE times, which would have triggered a response based on the system frequency, the AHU was shut off to observe the effect on the indoor air temperature within the zone, as shown in Figure 48. None of the previous grid events would have caused the indoor air temperature to drift outside of the temperature limits for the five-minute shutoff duration. As the longest previous grid event was less than five minutes, lasting for only three minutes and forty-six seconds, it is clear that no risk or unacceptable impact on the indoor air temperature would have occurred, therefore demonstrating that there would be no risk to the site if it were participating in a DR scheme during these events. To analyse the potential further, the AHU was set to remain off for longer durations for the same trigger points to assess how long it could safely remain off when responding to these grid events. The event that occurred on 3 March 2019 would not have encountered any risk across each of the shutoff durations; whereas the 8 May 2019 and 23 September 2020 events would have been
considered a risk only if, they were to remain off for an hour. As illustrated in Figure 48, the remaining grid event days each exceeded the upper temperature limit and would be considered a risk across the thirty, forty-five and sixty minute durations.

The comprehensive risk assessment results for each of the grid event days and shutoff durations are presented in Figure 49. This demonstrates the industrial AHUs performance capabilities and any potential risk to the indoor air temperature based on the thermal comfort threshold limits and the ASHRAE drift criteria of 2.2°C across a one-hour period and 1.1°C within this one-hour period or at any stage. As illustrated, none of the grid event days incurred any risk under these criteria for shutoff durations less than twenty minutes, which further highlights the low-risk potential for these assets to participate in DR schemes. The 24 April 2019 and 20 May 2019 events were the only grid event days to encounter any risk in the thirty-minute category, both caused by the internal air temperature exceeding the 23°C limit. There would be even lower levels of risk for their participation if the upper temperature limits were increased, as none of the shutoff durations were classified as a risk according to the ASHRAE temperature drift criteria during this analysis.
As part of the risk assessment, the temperature drift caused by each AHU shutoff for a grid event was analysed. Each event caused the indoor air temperature to drift by some amount as demonstrated in Figure 50; however, none of the modelled events exceeded the critical 2.2°C limit imposed by the ASHRAE standard. The event occurring on 3 March 2019 presented the lowest temperature drift of the days analysed, with a mean drift of only 0.7°C and with the largest drift value only reaching 1.5°C. This may be due to the event occurring early in the day and therefore being less influenced by external factors, solar gains and occupancy levels within the internal zone. The low risk to indoor thermal environments for AHUs participating in DR can be proven by the mean temperature drift across all events up to one hour in duration falling between 0.7°C and 1°C, which is well within the limits allowed by the ASHRAE standards. Furthermore, the median temperature drift of each of these events fell between 0.6°C and 0.9°C, as shown in Figure 50, which is also clearly within the allowable limits. The grid events incurring the largest drift range and variability were the 24 April 2019 and 20 May 2019 events. Both of these events occurred later in the day compared to some of the other events that also took place during the summer months, when higher risks of overheating may be expected. This result demonstrates that there is a lower level of risk when responding to grid events on the case study site before the lunch break rather than after it or broadly, that there is less risk to AHU DR participation in the earlier hours of the day.

<table>
<thead>
<tr>
<th>Shutoff Duration (min)</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>45</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>03/Mar/19 06:12:59</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>20/Mar/19 16:46:16</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>24/Apr/19 15:21:07</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>R</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>08/May/19 09:14:23</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>20/May/19 14:54:12</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>11/Jul/19 07:53:37</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>19/Jul/20 06:26:35</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>23/Sep/20 11:02:15</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
</tbody>
</table>

*Figure 49. Risk levels for each actual GFE day and shutoff duration analysed, with no risk events represented in green and any risk event that caused a risk by exceeding allowable temperature or drift limits coloured in red.*
5. Results, Impact & Discussion

5.2.5 Discussion of Modelling Results

Overall, the key findings of this study demonstrates that the case study site and associated industrial AHU deals predominantly with cooling and therefore, longer AHU shutoff durations lead to larger temperature drifts. This is particularly evident in Section 5.2.2 where the highest levels of risk to thermal comfort are demonstrated. The results presented here may be particularly valuable to industries considering participation in DR schemes, particularly the extreme weather scenarios, as they further emphasise the value of targeting the shorter duration, faster DR categories. These short duration responses present minimal risk to thermal comfort, with no demonstrated operational risk for any of the five-minute shutoffs on the case study site and only rare excursions outside of the risk limits during fifteen and thirty-minute shutoffs during the extreme hottest days assessed. This further highlights the significant low-risk potential available for industries to participate in these DR schemes safely. The industrial site would also receive the additional benefits through the incentive and payment structures provided to participants that emphasise and reward the more lucrative fast and short response categories. Equally, based on the results presented from assessing this AHU there is potential to target all of the response categories, thereby maximising the value to the grid and the site itself. By participating in the slower response but longer duration shutoffs, it would be possible to evaluate in advance the risk of participating in the event or even marginally pre-cooling the zone within allowable limits to ensure minimal impact on overall thermal comfort and prevent temperature drifts noticeable to the zone occupants. This would allow the industrial site participating in the response schemes to maximise their performance by opting to contribute to the short and long duration shutoffs. Furthermore, the potential has also been demonstrated to

![Figure 50. Box and whisker plot of indoor air temperature drift for all durations during each day a GFE occurred, with the median represented by a green horizontal line.](image-url)
Based on the results of this study, summarised in Table 2, it is evident that there is significant potential for industrial AHUs that serve buildings with low thermal inertia-high thermal response characteristics to be included in DR schemes. The evaluated operational risk to indoor thermal environments is also demonstrated to be at a low level, particularly in the case of the shorter duration shutoffs. To mitigate any potential operational risks further, industrial participants could work with the TSO or a DR aggregator to develop their asset availability criteria based on this research. For example, the potential industrial participant could define suitable limits for response availability. In this case, when the temperature is within certain bounded areas there will be no risk, meaning the response capacity is available and conversely if the $T_z$ is outside the known no-risk limits then the capacity is not available to respond. This process could easily be automated by combining the temperature readings from the site’s BMS with the frequency-monitoring device used to trigger the response. Additionally, a time-of-day response criteria could also be incorporated based on this study, particularly from the results shown in Figure 4. For industrial sites operating similar AHUs and occupancy schedules, it may be possible to target only events in the earlier hours of the day where the risk was demonstrated to be lower. Alternatively, the industrial participant could define its capacity as unavailable during the least low-risk hours of the day, which were shown to be roughly between 14:00 and 16:00 during a normal working day. Based on the defined performance requirements and contract conditions the participant could choose to opt out of responding to certain higher risk events, although this may incur financial penalties or, at the very least, missed revenue for potential performance. The risk-versus-reward relationship may prompt further analysis on a site-specific level. However, the minimal increase in risk would considerably improve any site’s financial benefits and the risk would generally be seen as acceptable in most cases.
### Table 21. Main statements from the modelling evaluations and analysis including key results and outcomes for each point.

<table>
<thead>
<tr>
<th>Statement</th>
<th>Key Result</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  The case study risk assessment evaluation deals predominantly with cooling.</td>
<td>Temperature drifts in a positive direction during AHU shutoffs.</td>
<td>Generally demonstrated more of an overheating than overcooling risk.</td>
</tr>
<tr>
<td>2  Longer AHU shutoff durations lead to higher risks.</td>
<td>No demonstrated risk for any of the 5-minute shutoff durations.</td>
<td>Short duration responses present minimal risk to the case study internal zone.</td>
</tr>
<tr>
<td>3  The longer the shutoff duration, the larger and more variable the temperature drift</td>
<td>Mean drift for 5 minute scenarios 0.2°C, min = 0°C and max = 0.3°C.</td>
<td>The shorter, faster and more lucrative response categories present lower levels of risk.</td>
</tr>
<tr>
<td>4  All response categories can be targeted by these systems</td>
<td>No risks encountered up to 20 minutes in the case study of actual previous GFEs.</td>
<td>All 5 frequency-response DS3 system services fall within 20-minutes, so would be suitable.</td>
</tr>
<tr>
<td>5  There is low-risk potential for industrial AHUs serving these building types to be included in DR</td>
<td>No case study risk was encountered in less than 30 minutes under TCR1. None of the assessed events exceeded TDR2 at any point.</td>
<td>Potential is available and this could be increased even further if setpoints were increased from 23°C to 24°C.</td>
</tr>
<tr>
<td>6  There is less risk responding to DR events earlier in the work day for industrial AHUs serving office spaces</td>
<td>The earliest shutoff time, 07:00, represented the lowest risk of overheating. The actual grid events that occurred later in the day were the only events to incur any risk in the 30-minute response scenario.</td>
<td>Time of day response criteria could be introduced to mitigate potential risks even further.</td>
</tr>
</tbody>
</table>

The modelling and analysis of the previous actual GFEs, as part of the evaluation of an industrial AHUs potential for DR, presented valuable insights and practical outcomes. The clear demonstration that even during these actual events no risk was encountered during the five-minute shutoffs for any of the scenarios studied further highlights the low risk of their participation. This realistic evaluation further emphasises the low risk and minimal impact on the indoor thermal environment, helping to build confidence in their performance and contributing to the reduction in perceived risk, which will help to overcome the barriers to industrial engagement in DR programmes. The illustrated ability for this industrial asset to respond and remain off for at least twenty minutes, as shown for each of the previous grid events in Figure 49, further compound its low-risk status and strong DR potential. This significant risk-free operating period for response allows the participants and TSOs the additional flexibility to provide the optimal response across the variety of DR categories, tailored to the specific needs required by the grid during any eventuality. This flexibility and
5. Results, Impact & Discussion

DR potential may be further increased on sites less influenced by standards and defined drift limits or with marginally less stringent temperature thresholds. If the upper thermal comfort threshold limits were increased from 23°C to 24°C, only a sixty-minute shutoff during the two previous grid events, 20 May 2019 and 24 April 2019, would have been classified as a risk. Furthermore, as occupant thermal comfort is transient, the shorter durations outside of the limits may not actually be perceived in practice and therefore may not need to be classified as a risk in every case. In the highly validated industrial sector, this less defined operating practice may cause further reservations, however a short offline trial ahead of commitment to participation could quickly obtain the empirical data required to demonstrate this point. This evaluation may even be achievable by analysing the occupant thermal comfort during a planned AHU shutdown or potentially during times outside the normal operating schedule where occupants may remain in the office space. The incremental temperature limit or allowable drift may not be acceptable on especially risk-averse sites, but the potential performance gains would be very significant where suitable, as this would allow greater flexibility and a risk-free response horizon of at least an hour in the majority of scenarios considered.

5.3 Impact and Scaling

The objective of this section is to evaluate a number of different scenarios to which this concept may be applicable and scalable to gain a deeper understanding of the potential impact of increased industrial participation in national DR programmes. This is especially aligned with the research output, to quantify and highlight the potential benefits of selected industrial assets deemed as low risk being incorporated into DR programmes and illustrate their potential impact on the Irish national electricity grid (RO4). Through implementation of the novel framework on a representative case study site in Chapter 4, it was found that it is realistic to expect between 35 kW to 75 kW of consistent flexible capacity from AHUs alone on industrial sites. This flexible capacity potential can be used to demonstrate the potential of this concept on an individual site, local, regional and national scale to illustrate the impact potential on the wider electricity grid. The national impact, if this flexible capacity were made available on a number of other similar industrial sites can also be analysed by scaling this single site figure up to representative company groupings. Additionally, the financial and environmental benefits to the participating site and impact on national emissions targets can also be analysed and highlighted. This includes the financial benefit to a site that can offer additional capacity on
top of the lowest risk asset capacities in addition to the dual benefits associated with this concept.

5.3.1 Scaling Scenarios

Following the initial framework implementation on the representative case study industrial site, it is possible to scale the realistic outcomes expected from this individual site up to larger grouping of similar industrial sites. The wider impact and potential of this concept can then be illustrated by typical industrial groups, such as local area aggregations or large scale national initiatives. An interesting small-scale depiction of the Irish manufacturing sector is presented by the Cork Lower Harbour Group (CLHG), with a number of similarly sized multinational companies within the same sector. The CLHG is made up of DePuy Synthes, Thermo Fischer, Janssen Biologics and Novartis, as demonstrated in Table 22, with each site located reasonably close to Ringaskiddy in the Cork lower harbour area, illustrated in Figure 51. Each of these buildings have AHUs similar to the case study site and it would therefore be reasonable to assume that a comparable capacity would be achievable on each site within this compilation.

Table 22. Overview of potential industrial groupings to which this concept could be implemented in and scaled within the Irish industrial sector.

<table>
<thead>
<tr>
<th>Grouping</th>
<th>CLHG</th>
<th>Cork Area</th>
<th>LIEN 1</th>
<th>LIEN 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential Companies</td>
<td>DePuy Synthes, Thermo Fischer, Novartis, Janssen Biologics, Pfizer</td>
<td><strong>Ringaskiddy</strong> (DePuy Synthes, Hovione, Thermo Fischer, Novartis, Janssen Biologics, Pfizer)</td>
<td><strong>Carritgwohill</strong> (Gilead Sciences, Stryker, AbbVie, GE Healthcare, Merck)</td>
<td><strong>Little Island</strong> (PepsiCo, Janssen Pharma, Pfizer)</td>
</tr>
<tr>
<td>Companies</td>
<td>4</td>
<td>16</td>
<td>69</td>
<td>199</td>
</tr>
</tbody>
</table>

Further to this small aggregation of four companies, the next step up for scaling potential captures several equally representative large companies within the industrial sector across the Cork Area. This collection includes the companies from the Ringaskiddy area, with a few additions, as well as further representatives from Carritgwohill, Little Island and Model Farm Road industrial estates, each of which are home to some of the largest companies within the industrial sector close to Cork city, in the south of Ireland. The remaining two categories for scaling potential, outlined in Table 22 and illustrated in Figure 51, are selections based on the Irish LIEN group. The first of these accounts for only the Pharma/Chem and Healthcare companies, of which there are 43 and 26, respectively, as they are more closely related to the case study site. The final grouping contains all of the 199 companies currently part of the LIEN,
of which the proclaimed message is to work together to improve their energy performance and inspire others to follow, making them a group that is well suited to adopt this concept. Based on the single-case study site and each of these potential groupings, it is possible to provide a detailed analysis of the potential achievable on a national scale. These capacity figures will help to develop the understanding of the potential impact and benefits of advancing the industrial sector’s participation in DR schemes using the presented framework.

5.3.2 Scaling Scenario Results

The case study site implementation and evaluation found and demonstrated that there was realistic, low-risk potential of approximately 35 kW to 75 kW available from a single industrial site. Based on these figures, it was possible to scale up the impact of this concept into the representative low and high potential capacity figures presented in Table 23. The first two groupings of the CLHG and the companies within the Cork area offer a reasonably conservative

Figure 51. Illustration of potential scenario groupings that this concept could be scaled to within the Irish industrial sector.
capacity to the national grid, with neither grouping exceeding 2 MW. The high potential Cork area capacity of 1.2 MW does present a useful local response capacity however, particularly in the case of regional grid issues or challenges caused by the electrical hub of Cork city. If this concept was adopted by either of the LIEN grouping scenarios, a considerable impact and numerous benefits could be provided to the national electricity grid. Additionally, if this were implemented across the entire LIEN, the high potential figure would provide close to 15 MW of flexible capacity to the grid, which could be a vital addition to the current control and reliability measures available to the TSOs.

<table>
<thead>
<tr>
<th>Grouping</th>
<th>Single Site (kW)</th>
<th>CLHG (kW)</th>
<th>Cork Area (kW)</th>
<th>LIEN 1 (kW)</th>
<th>LIEN 2 (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Potential</td>
<td>35</td>
<td>140</td>
<td>560</td>
<td>2415</td>
<td>6965</td>
</tr>
<tr>
<td>High Potential</td>
<td>75</td>
<td>300</td>
<td>1200</td>
<td>5175</td>
<td>14,925</td>
</tr>
</tbody>
</table>

Each of these individual scenarios offer value of varying scales both financially to the specific sites and to the wider electricity grid in terms of providing useful flexible capacities. The impact of each low and high potential scenario is illustrated in Figure 52, compared to a variety of actual existing capacities participating in the Irish national grid for context. Two windfarms within the Electricity Supply Board (ESB) generation portfolio that offer comparable generation capacity figures were selected. Carnsore windfarm has fourteen turbines, offering 11.9 MW, and Grouselodge windfarm has six larger turbines, offering 15 MW of capacity to the grid [249]. The Indaver Waste-to-Energy (WTE) steam turbine offers 17 MW of generation capacity [20], 15.1 MW of which is exported to the national grid [250]. The Existing Industrial Capacity of 9 MW, made up of small-scale generators used for supply during peak demand or similar circumstances, is also of comparable size [20]. Finally, the Statkraft 11 MW, 5.6 MWh lithium-ion Battery Energy Storage System (BESS) in Kilathamoy, Co. Kerry [251], already contracted for DS3 system services, provides an interesting comparison to the scaling scenarios as they could potentially fall in the same response categories.
Both the low and high potential capacities offer a useful fraction of each of these capacities to the grid and therefore could offer valuable flexibility in the event that any of these examples encountered issues causing their output to fluctuate. The high potential LIEN 2 scenario could replace in full the Existing Industrial Capacity, the Statkraft BESS or Carnsore windfarm if they were to go offline suddenly with capacity to spare. It could also replace a significant segment of the output from the Indaver WTE plant or Grouselodge windfarm in the event of an unexpected issue or sudden loss of generation resources. This would allow the grid to recover and quickly replace this capacity seamlessly, eliminating the risk of frequency events and even blackouts, which may not be achievable in the future with the current levels of connected flexible capacity. Furthermore, this capacity grouping could form part of a larger existing or planned VPP, or through additional organisation even become a VPP in its own right, if the coordination or demand for this was high enough. These aspects may become increasingly important in the future as EirGrid continues to decommission older and higher CO₂ emitting power plants from the grid [20]. The additional flexible capacity would help to mitigate any adequacy issues and prevent increased strain as the levels of RESs on the grid increase, creating even more need for the DS3 system services on the Irish national grid.
5.3.3 Additional Detailed Scaling Scenarios

To evaluate the impact and potential for this concept further within the wider industrial sector, a number of additional scenarios are presented to deepen the understanding of the available potential. The additional scenarios presented in this section are based on common industrial assets that would generally be found across the sector, particularly on sites similar to the case study building. Each of the included assets were identified on the case study site during the evaluation, eventually being ranked in the Level 1 or Level 3 categories, as illustrated in Section 4.2.4 Table 12 and Figure 32. The first of these scenarios, labelled AHU in Table 24, captures the increased capacity if an industrial site were able to include five other AHUs in addition to the low or high potential capacities previously identified.

Table 24. Overview of potential additional industrial asset scenarios that could be included to increase flexible capacity aggregations on industrial sites.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>AHU</th>
<th>Chiller 1</th>
<th>Chiller 2</th>
<th>AHU &amp; Chiller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asset Type</td>
<td>AHUs</td>
<td>Chillers</td>
<td>Chillers</td>
<td>AHUs &amp; Chillers</td>
</tr>
<tr>
<td>No. Assets</td>
<td>5</td>
<td>1</td>
<td>2 / 3</td>
<td>3 &amp; 2 / 3</td>
</tr>
<tr>
<td>Capacity (kW)</td>
<td>75</td>
<td>100</td>
<td>150</td>
<td>195</td>
</tr>
</tbody>
</table>

The following two additional capacity aggregations are based on a site including chiller capacity to their response portfolio. These industrial assets were selected for additional demonstration scenarios, as they were the next lowest ranking-level asset located in the same plant-room nearby to the included AHUs on the case study site. Thus, making them suitable in terms of connectivity and ease of practical inclusion in the flexible capacity portfolio. The chillers on the case study site are also operated in combination, so one or more of these assets could be shut off in response and there would still be some supply to the main header. Although the supply would be at reduced capacity for the duration of the event, this would further mitigate the risk of one of these chillers being included in the response portfolio. Furthermore, based on onsite SME experience there is suitable buffer capacity or inertia in the overall system to allow these assets to be quickly shut off for DR, in addition to other previous studies also demonstrating these potential capabilities [41][252][253]. The Chiller 1 scenario represents the inclusion of 100 kW of chiller capacity, similar to that of a chiller identified on the case study site. The Chiller 2 scenario represents the addition of 150 kW of chiller capacity to the aggregated response. In practice, this could be achieved in a number of ways, for example including a larger 150 kW chiller, 75% of two 100 kW chillers or 50% of three 100 kW chillers, similar to ramping down a chiller like the one identified on the case study site. The final scenario, AHU & Chiller shown in Table 24, illustrates the capacity achievable on a site
presenting three additional AHUs and 150 kW of chiller capacity to participate in a DR programme. Each of these scenarios present potential flexible capacity aggregations that could be made available from an industrial site. These will be further evaluated and discussed to highlight the potential impact achievable through their participation as outlined in RO4.

5.3.4 Additional Detailed Scaling Scenario Results
Following the implementation of the proposed framework on the representative case study site in Chapter 4, it was found and demonstrated that there was realistic, low-risk potential of approximately 35 kW to 75 kW available from a single industrial site. There is likely much higher potential available throughout the industrial sector, particularly if marginally higher levels of risk were to be tolerated or additional low-risk assets are actually available on larger sites. Examples of possible larger aggregations, outlined in the previous section, are presented in Table 25, where the initial baseline low and high potential capacity figures are combined with the additional four industrial asset scenarios as an overall capacity figure. These flexible capacity figures available from a single site are also scaled up to the LIEN 1 grouping previously outlined, which includes 69 of the largest Irish industries most comparable to the case study site. This industrial group is made up of 43 large pharmaceutical and chemical companies and 26 healthcare companies as previously discussed. This grouping contains industrial sites with comparable building thermal characteristics and where similar assets and capacities would be present, therefore ensuring the framework and modelling outputs remain representative to scale up to this industrial group.

Table 25. Demonstration of the low and high potential capacities achievable by a single site and the LIEN 1 group of companies across the four potential industrial asset scenarios.

<table>
<thead>
<tr>
<th></th>
<th>Single Site</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AHU</td>
<td>Chiller 1</td>
<td>Chiller 2</td>
<td>AHU &amp; Chiller</td>
</tr>
<tr>
<td>Low Potential</td>
<td>110 (kW)</td>
<td>135 (kW)</td>
<td>185 (kW)</td>
<td>230 (kW)</td>
</tr>
<tr>
<td>High Potential</td>
<td>150 (kW)</td>
<td>175 (kW)</td>
<td>225 (kW)</td>
<td>270 (kW)</td>
</tr>
<tr>
<td>LIEN 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Potential</td>
<td>7590 (kW)</td>
<td>9315 (kW)</td>
<td>12765 (kW)</td>
<td>15870 (kW)</td>
</tr>
<tr>
<td>High Potential</td>
<td>10350 (kW)</td>
<td>12075 (kW)</td>
<td>15525 (kW)</td>
<td>18630 (kW)</td>
</tr>
</tbody>
</table>

The scenarios outlined in Table 25 present examples of potential larger aggregations on an industrial site that would be available on similar sites to the case study. As demonstrated, from the addition of five more similar AHUs the site could present over 100 kW of flexible capacity, which has been demonstrated as having very low to no impact or operational risk. Both of the chiller scenarios offer additional useful flexible capacity figures, between 135 kW and 225 kW,
through the combination of the lowest risk AHUs and a single or combination of multiple chiller capacity reductions. Either of these high or low potential scenarios considerably boost the overall capacity figure, ensuring the participant receives larger payments and importantly for decisions makers, more reward for any perceived risk. The final scenario, contributing an additional five AHUs and a combination of chiller capacities to the low or high baseline capacity available results in a notable aggregation of 230 kW to 270 kW. This response capacity represents a valuable contribution from an individual site that would certainly warrant inclusion in a wider DR aggregator’s response portfolio or presented outright from the site to the TSO. The low and high potential capacities available if these individual site scenarios were implemented on each of the LIEN 1 group of companies are also presented in Table 25 and illustrated in Figure 53, demonstrating the potential available in these cases. Considerable impact could be achieved through implementation of this concept, as each of the potential scenarios offer over 7.5 MW of flexible capacity to the grid and up to approximately 18.5 MW with the high potential AHU & Chiller scenario.

![Figure 53](image)

*Figure 53. Bar chart illustrating the low (Yellow) and high (Blue) potentials achievable if each of the four scenarios were implemented throughout the LIEN 1 group of companies.*

Each of these scenarios could be invaluable to the TSOs in relation to the impact presented in Section 5.3.2 compared to existing capacity figures on the grid. They would also be valuable additions to the existing total DS3 contracted volumes from all sectors in Ireland where these
capacities could participate. These are between 810 MW and 1840 MW in the five response categories from Fast Frequency Response (FFR) to Tertiary Operating Reserve 2 (TOR2) [254]. The largest scenario capacity of approximately 18.5 MW would represent almost 2.3% of the existing FFR capacity and nearly a fifth of the submitted capacity in the most recent capacity auction [254]. This same scenario could also provide an additional 1% to the largest of the five DS3 categories, TOR2, which would also amount to approximately 20% of the most recently submitted volumes [254]. Furthermore, as these capacities are achieved through implementation on only the 69 companies of the LIEN 1 group, it may be more feasible to expect this uptake in practice. However, if the AHU & Chiller scenario were to be implemented throughout the LIEN 2 group of companies, the potential is there for approximately 45.7 MW to 53.7 MW of flexible capacity, which would have a significant impact on the TSOs ability to maintain reliable control of the national electricity grid. This would also increase the capacity submission for each of the five DS3 categories discussed by almost half, which would represent a significant impact within this area.

5.3.5 Financial Performance and Incentives

In addition to the valuable resource provided to the TSOs, there are also lucrative incentive payments available to participants for engaging in the DR programmes, previously identified as a driving factor. There are no stated minimum capacity thresholds for participation in the DS3 system services in Ireland, only participation capability stipulations and minimum data requirements, so the main financial consideration for potential participants is the cost-effectiveness of their participation. Evaluating the potential revenue streams and demonstrating the potential financial gains achievable through the incentive structures provides a useful illustration for any potential participants and may help to drive further industrial engagement in these DR programmes. The annual availability payments for a single site, excluding additional bonuses or payment scalars, for the low and high potential capacities of 35 kW and 75 kW respectively demonstrate the baseline expected potential in Table 26. These initial payment figures are noteworthy as they represent realistic capacities available from any Irish industrial site, proven to present low to no-risk operational risk to the participant. Emphasised by the previous demonstration of no operational risk to the site for at least twenty minutes during previous actual GFEs, shown in Section 5.2.4. Figure 49, which captures the full elapsed time of each of the DS3 system services presented in Table 26. The Primary Operating Reserve (POR) system service category offers the highest potential earnings and appears to be the most valuable system service to both the participant and wider national grid. A single site has the
potential to earn a base annual participation payment of €993 for only 35 kW and up to €2129 for a higher potential capacity of 75 kW by participating in this particular category alone.

*Table 26. Annual payments achievable by a single site offering low and high potential capacities for each of the five individual frequency response DS3 system services.*

<table>
<thead>
<tr>
<th>DS3 System Service Category</th>
<th>Delivery Time (s)</th>
<th>Low Potential 35 kW (€)</th>
<th>High Potential 75 kW (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Frequency Response (FFR)</td>
<td>2 – 10</td>
<td>662</td>
<td>1419</td>
</tr>
<tr>
<td>Primary Operating Reserve (POR)</td>
<td>5 – 15</td>
<td>993</td>
<td>2129</td>
</tr>
<tr>
<td>Secondary Operating Reserve (SOR)</td>
<td>15 – 90</td>
<td>601</td>
<td>1288</td>
</tr>
<tr>
<td>Tertiary Operating Reserve 1 (TOR1)</td>
<td>90 – 300</td>
<td>475</td>
<td>1018</td>
</tr>
<tr>
<td>Tertiary Operating Reserve 2 (TOR2)</td>
<td>300 – 1200</td>
<td>380</td>
<td>815</td>
</tr>
</tbody>
</table>

The annual payments achievable for a participating site under each of the four scenarios, including low and high potentials for each AHU, chiller or combination scenarios, are demonstrated in Table 27. This table outlines the revenue streams available for participating in each of the five frequency response DS3 system services individually, where again the POR category offers the most reward. For an industrial site prepared to offer the low potential AHU only scenario to participate in each of the five DS3 system services, they would expect to receive an annual payment of €9781 or approximately €815 each month. Similarly, if an industrial site were to offer the high potential AHU & Chiller scenario to the grid, they would receive €24,007 annually, which equates to payments of approximately €2001 each month. In the industrial setting, if a site consumed 2,000,000 kWh each month in 2020, where the average unit price was €0.09648, which is comparable to the case study site, then the lowest potential scenario presented would amount to almost 0.5% of the site’s annual electricity bill, excluding any potential bonus or additional incentive payments. Comparatively, for the largest capacity scenario, AHU & Chiller high potential, in the same case the site would expect to receive base payments, excluding additional earnings, of more than 1% of their total annual electricity expenditure.
Table 27. Annual payments achievable for the four scenarios offering low and high potential capacities under the five frequency response DS3 system services.

<table>
<thead>
<tr>
<th>DS3 System Service</th>
<th>AHU Potential Low (€)</th>
<th>AHU Potential High (€)</th>
<th>Chiller 1 Low (€)</th>
<th>Chiller 1 High (€)</th>
<th>Chiller 2 Low (€)</th>
<th>Chiller 2 High (€)</th>
<th>AHU &amp; Chiller Low (€)</th>
<th>AHU &amp; Chiller High (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFR</td>
<td>2081</td>
<td>2838</td>
<td>2554</td>
<td>3311</td>
<td>3500</td>
<td>4257</td>
<td>4352</td>
<td>5109</td>
</tr>
<tr>
<td>POR</td>
<td>3122</td>
<td>4257</td>
<td>3832</td>
<td>4967</td>
<td>5251</td>
<td>6386</td>
<td>6528</td>
<td>7663</td>
</tr>
<tr>
<td>SOR</td>
<td>1889</td>
<td>2575</td>
<td>2318</td>
<td>3005</td>
<td>3176</td>
<td>3863</td>
<td>3949</td>
<td>4636</td>
</tr>
<tr>
<td>TOR1</td>
<td>1494</td>
<td>2037</td>
<td>1833</td>
<td>2376</td>
<td>2512</td>
<td>3055</td>
<td>3123</td>
<td>3666</td>
</tr>
<tr>
<td>TOR2</td>
<td>1195</td>
<td>1629</td>
<td>1466</td>
<td>1901</td>
<td>2010</td>
<td>2444</td>
<td>2498</td>
<td>2933</td>
</tr>
</tbody>
</table>

A participating industrial site can also maximise their financial benefit through payment multipliers called scalars. One of these scalars offers 1.5 times the FFR payment for a site that is capable of providing a suitable fast response and remaining off, for the continuous provision of a response until the TOR1 category is satisfied [255]. This means responding within two seconds and maintaining this response for five minutes, which would result in an annual payment of €3063 or €6563 for a site offering 35 kW or 75 kW of response capacity, respectively. This provides considerable opportunities for industrial AHUs if they can be set up to meet these requirements, as they have proven their ability to remain off for the specified duration, incurring no impact to their served area on the site. Further financial benefits can be achieved through these payment scalars with the larger capacity scenarios outlined in Table 27 and illustrated in Figure 54. As highlighted by the first dark square in this figure, Scalar 1, the low potential AHU scenario could expect to receive €9626 for responding to the FFR signal and remaining off throughout the first four DS3 system services. By remaining off for the final system service, TOR2, which is also within the demonstrated low to no operational risk threshold, the site could receive €10,821 annually as highlighted by the first green triangle, Scalar 2, on the secondary axis of Figure 54. Furthermore, capturing the same benefits from the payment scalar structure, a site presenting flexible capacities to the scale of the AHU & Chiller high potential scenario could expect annual payments of up to €23,628 under Scalar 1 conditions and as much as €26,561 under the Scalar 2 conditions. Each of these examples represent the considerable financial gains achievable through increased performance and the value of the incentive payment multipliers. For the low potential AHU scenario, it would now be able to achieve between 5 and 6% of its annual electricity bill under Scalar 1 and 2 conditions if it were consuming approximately 2,000,000 kWh per month in 2020. Whereas the same site presenting capacities like the AHU & Chiller high potential scenario, could expect to receive payments of between 12 and 14% of its equivalent annual electricity bill under Scalar 1 and 2
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conditions. This potential financial performance offers a clear demonstration of the benefits of industrial DR participation, particularly with these low-risk assets, which outline the impact and significant value of increased industrial engagement in these programmes.

EirGrid also offer other payment scalars for participating in the DS3 system services to incentivise further participation, particularly during times most needed by the TSOs to maintain reliable control of the grid. One of these other payment scalars is linked to the system SNSP at the time of the response, which essentially means the participant receives higher payments based on the amount of renewables on the grid at the time of the event. According to the DS3 system services scalar design document [255], a scalar of 6.3 should be applied for SNSP levels above 70% and 4.7 when the SNSP level is between 60 and 70% during times a response is required. This factor considerably incentivises additional participation in these schemes, as shown by the impact on annual payments if a site provided all five DS3 system services and each response occurred within the outlined SNSP zones under the scenarios as presented in Table 28. This payment strategy is clearly aligned with the overall goal to continue increasing the national grid’s SNSP levels above 70% consistently to meet national targets. There is clearly a heavy incentive for additional performance during these times, as even the lowest scenario of a site presenting only 35 kW, Base Low Potential, has the potential to earn €21,692 if each of its response events occur during times that the system SNSP level is above 70%. Even higher payments are captured under the AHU & Chiller High Potential scenario, where...

Figure 54. Annual payments achievable by each capacity scenario in each of the five frequency response DS3 system services discussed, with payments achievable through scalar bonuses on the secondary axis.
the site would expect to receive €124,838 annually if each of their response events occurred with the SNSP between 60% and 70% and even €167,336 if all of the events were above 70% SNSP. This demonstration clearly outlines the significant financial performance achievable through industrial participation in DR and highlights the impact this engagement could have on a participating industrial site.

Table 28. Annual payments achievable by a participating site under four varying scenarios if each of the scalars were captured and the response events all fell within one of the three SNSP level categories.

<table>
<thead>
<tr>
<th>SNSP Level</th>
<th>Scalar</th>
<th>Base Low Potential (€)</th>
<th>Base High Potential (€)</th>
<th>Chiller 1 Low Potential (€)</th>
<th>AHU &amp; Chiller High Potential (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNSP ≤ 60%</td>
<td>1</td>
<td>3443</td>
<td>7378</td>
<td>13,281</td>
<td>26,561</td>
</tr>
<tr>
<td>SNSP &gt; 60% and ≤ 70%</td>
<td>4.7</td>
<td>16,183</td>
<td>34,677</td>
<td>62,419</td>
<td>124,838</td>
</tr>
<tr>
<td>SNSP &gt; 70%</td>
<td>6.3</td>
<td>21,692</td>
<td>46,482</td>
<td>83,668</td>
<td>167,336</td>
</tr>
</tbody>
</table>

The financial incentive structures and payment schemes are designed to encourage sites to participate in DR and the DS3 system services, assisting the safe and reliable management of the national electricity grid. This has a two-fold benefit as a site receives payment for participation but also reduces its electricity consumption during these events. By definition, the grid is usually under considerable stress during these events, which generally equates to higher unit prices for electricity during these times. A participating site would be able to reduce its demand for electricity during these events and therefore lower its overall electricity costs. Furthermore, as the incentive structures are based on availability, participants will still receive this base payment whether they are called to respond numerous times, only once or even not at all, depending on the grid requirements each year. Limitations can also be placed on the frequency of responses, with some contracts ensuring that a site will not be called to respond twice in the same month. Similar stipulations or performance limitations can be included based on the participant’s requirements or specific requests and the contractor or TSO’s ability to facilitate these, which further reduces any potential hesitation or possible risk of participation.

5.3.6 Dual Benefit Analysis
To capture the value and benefits achievable from industrial DR implementation fully, it is important to analyse the dual benefits of this practice, which were identified as an additional driving factor for this concept. This benefit can be illustrated in a number of scenarios and through a variety of different metrics. The most prominent indicator of value is the financial performance, which can be highlighted through the incentive payments received as previously discussed and the avoided cost of electricity caused by the capacity reduction during a DR
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Another valuable benefit of DR participation is the reduction of CO₂ emissions. This is integral to the overall DS3 programmes goals and ability for the wider national grid to maintain reliable control while reducing overall CO₂ emissions, although it may not be as significant on an individual site level it is worth quantifying and capturing. These emission reductions can be achieved through reduction in overall grid emissions by facilitating additional RESs and the emissions avoided on a site level by reducing consumption during the DR event. To put this into context, an industrial site participating in DR in 2019 that is presenting 270 kW of flexible capacity, equivalent to the AHU & Chiller High Potential scenario previously discussed, is illustrated in Figure 55. This example site consumes approximately 1,000,000 kWh per month when the unit price was approximately €0.096, the site responded to each of the actual DS3 grid events for one hour where the SNSP limit was greater than 70% and the 2019 grid electricity emissions factor was 324.5 gCO₂ per kWh [256].

![Figure 55. Waterfall diagram of example site annual electricity bill with No DR (grey) and With DR (blue), payments received are highlighted in light green and cost savings are illustrated in dark green.](image)

As illustrated, the incentive schemes amounted to an annual payment of €167,336 and the site was able to save €234 in electricity not required from the grid during these events. These combined savings resulted in the overall annual electricity bill for the industrial site being reduced from €1,157,760 to €990,190, or a total annual electricity bill reduction of €167,570. This represents a financial resource for an industrial site worth capturing and based on this demonstration may encourage additional uptake of DR in the industrial sector. The increased flexible capacity made available to the TSOs that this represents would have an impact on their
ability to maintain control of the electricity grid as levels of RESs increase to meet national emissions targets [20]. Furthermore, considering the emissions factor of grid electricity for the year this example site was participating, this individual site would have meant that approximately 1.34 tonnes of CO$_2$ would not have been produced between the site and national grid. This additional benefit results from the extra renewable energy the grid could facilitate during this year, amounting to almost 552 kg of CO$_2$ emission savings. The site itself was also able to reduce its CO$_2$ emissions by almost 789 kg for that participating year due to the embodied emissions of the electricity it was able to reduce while responding to the actual DR events. The dual benefit of this concept presents an even more encouraging prospect to potential industrial participants and this demonstration highlights the significant impact it can have through further widespread implementation within this sector.

5.3.7 Discussion of Impact and Scaling Results

This chapter presents an overview demonstration of the low operational risk to industrial participants, illustrations of the potential impact of individual and scaled implementation of this concept in the industrial sector and analysis of the potential performance benefits to an individual site. The potential capacities achievable through implementation of this concept, as previously discussed, offer a number of interesting and increasingly valuable benefits to the national electricity grid. The 35 kW to 75 kW capacity expectation may vary across different site, with various processes, configurations and plant sizes. However, it provides a suitable illustration of a representative range of participation capabilities across a large collection of industrial sites. Thus, allowing sites with significantly higher and exceptionally lower suitable capacities to be captured within one grouped figure that represents the potential impact of the LIEN adopting the concept in this case. The potential capacity scenarios illustrated in Figure 52 demonstrate the impact in relation to existing generation sources of similar scale; however, the additional flexible capacity available in this sector may also have a greater impact on the national grid in the longer term or through greater uptake, as illustrated in Figure 53. Currently, the impact of data centres in Ireland is an especially topical issue and the potential capacities of this concept may benefit the TSOs with some aspects related to this issue. Data centres are generally considered a stable base load demand on the grid and so TSOs will often incorporate further variable renewable sources of energy onto the grid on the basis that these data centre capacities will remain static. While the potential capacities of this concept are not directly comparable to some of the bigger data centres, like the 108 MW Facebook data centre in Clonee, Co. Meath, currently the largest in Ireland [257]. They are larger than the capacities of ten of
the existing data centres in Ireland, including the 4 MW CIX-Cork Internet eXchange data centre in Co. Cork [257]. This means they would be capable of responding to any grid fluctuation or disturbance caused by an issue at one of these data centres causing them or a fraction of the larger data centres loads to suddenly drop off or re-join the grid demand unexpectedly.

In addition to providing valuable flexible capacity to maintain control of the grid during fluctuations caused by data centres, among other issues, this concept can also help to smooth the transition away from some of the highest emission fossil fuel generators. The increased controllability afforded to the grid TSOs can reduce the pressure to repair traditional fossil fuel plants or return outdated peaking plants into the generation pool. The two combined-cycle gas turbine plants in Whitegate, County Cork and Huntstown, County Dublin were recently fast-tracked for repair at great cost, due to fears of supply shortfalls and even blackouts on the Irish grid during the winter period. Although the potential capacity scenarios are not directly comparable to the respective capacities of Whitegate’s 450 MW and Huntstown’s 745 MW, which are made up of two 337 MW and 408 MW gas turbines [20]. The additional ability to maintain control of the grid at higher levels of renewable penetration and with the remaining electricity supply still online, the urgency to repair or upgrade these large fossil fuel plants is reduced. Furthermore, increasing the grid’s resilience and controllability allows the TSOs to maintain or increase the rate at which older, less efficient plants are decommissioned and removed from the generation mix. Replacing the need for fossil fuel plants used only for peak demand times or other similar scenarios would help to decrease the reliance on carbon-intensive fuels and minimise national emissions in line with international targets.

The impact of this concept is significant in the industrial sector, particularly as the expected scenarios and capacities available are demonstrated to present low to no operational risk to participating sites. The low-risk levels of the expected 35 kW to 75 kW are especially encouraging for the continued uptake of this concept as the marginally higher levels of risk they demonstrated only occurred during the worst-case scenarios or 99th percentile daily weather profiles. This demonstration should minimise the perceived risk associated with this concept and help to encourage additional industrial participants, as it can largely be viewed as a low to no risk endeavour with notable income and cost reduction potential. Even in the case of smaller potentials that may not immediately appear as financially viable, the flexibility of this concept may allow these capacities to be included virtually as participants in dispersed grid aggregator portfolios or as part of a wider VPP. This may eventually allow smaller industries
to participate with a local aggregation of other industrial sites or even commercial or residential
groups to offer larger flexible capacities to the TSOs. These aggregations or possible VPPs
would provide valuable services to the national grids and benefit each of the stakeholders
impacted by their performance. The performance of these potential aggregations may also be
further influenced by developments with the incentive payments structures in the future. The
TSOs are generally heavily engaged with their participants, which may result in further
incentives being introduced in the future. One such aspect is the SNSP scalar, which currently
offers considerable benefit for responses above 70% SNSP. However, as the system advances
and these levels become commonplace, the next step may be to incentivise responses above
80% or higher levels of SNSP further. This may be required in the future as higher levels of
RESs, possibly over 90% grid SNSP at times, will be necessary to meet national emissions
targets. On an individual site level, the dual benefits of this concept may also play a role when
it comes to carbon neutral planning and certain sites achieving their corporate goals and internal
targets. The additional CO\textsubscript{2} offsetting and quantifiable emission reduction capabilities of DR
participation mean this concept could be utilised to benefit a site’s green image or as a useful
component in a wider carbon neutral plan to fully avail of its embodied benefits.

5.4 Conclusions
The research and results presented in this chapter offer a number of outputs and new knowledge
in this area. The implementation of the proposed framework helped to identify industrial assets
for participation in DR and the utilisation of the practical risk assessment modelling-tool further
helped to illustrate elements that influence operational risk, which helped to reduce some of
the perceived risk previously identified as a barrier to the uptake of this concept. Demonstrating
the low risk of the identified assets participating in DR programmes should help to encourage
additional industrial engagement and participation in these schemes. The development of this
risk-assessment modelling tool and subsequent evaluations conducted directly fulfil the
requirements of RO3 and provide novel results to enhance the understanding of industrial
performance in this area. Basing the modelling tool analysis on common temperature
thresholds and the defined ASHRAE 55 temperature drifts limits ensured an industry proven
assessment was conducted. To ensure a suitable evaluation was conducted, actual empirical
temperature measurements, historical hottest and coldest daily temperature profiles and
predicted 99\textsuperscript{th} percentile hottest and coldest future days were assessed. The inclusion of
predicted future hottest and coldest Budapest daily temperature data, which is representative
of an extreme European climate, increased the international relevance of this evaluation. The results of this modelling risk assessment demonstrate that there is generally very low operational risk of these industrial assets being included in DR programmes.

It was demonstrated that there is more risk of overheating than overcooling events occurring on the case study site, although no risk was still the most common result through all of the scenarios analysed. This analysis identified that there is very little risk of these assets participating in the shorter duration events, especially five-minute shutoffs, even in these most extreme case study scenarios. Furthermore, across all of the scenarios conducted, none of the events caused the temperature drift to exceed TDR2 conditions at any point, which would be a temperature drift of more than 1.1°C in a fifteen-minute period and would potentially be the most noticeable impact to the occupants. By assessing the previous actual grid events, it was demonstrated that no operational risk would have been encountered when shutting off for five-minutes in response to any of the previous GFEs analysed. During this analysis it was also demonstrated that the case study AHU could have remained off, incurring no operational risk, for at least twenty-minutes in each simulated case. Generally, it was demonstrated that there is lower risk of participation in events occurring earlier in the day and that possible risk levels could be further mitigated by increasing upper temperature limits. This is clear as if the upper temperature limit was increased from 23°C to 24°C or the boundaries were more closely linked to perceivable thermal comfort levels then only two of the previous actual grid events would have registered any risk and only during a one-hour shutoff response. These results represent positive findings for the inclusion of these industrial assets in DR and illustrate the low levels of operational risk associated with their participation, helping to overcome the perceived risk that was previously identified as a barrier to its implementation.

Following this analysis, it was possible to evaluate the potential of this concept and including low-risk industrial assets in DR to assess its impact on the Irish national grid. By fulfilling the intention of RO4, it is possible to demonstrate the clear impact potential of this concept if it were to be adopted and further implemented within the wider Irish industrial sector. As outlined in Chapter 4, it is realistic to expect between 35 kW to 75 kW of flexible capacity from AHUs on a single industrial site. If these capacities were provided by each of the 199 largest industrial companies in Ireland, within the LIEN group, then the flexible capacity resource available to the national TSO would be between 7 MW and 15 MW, which could have a considerable impact. The higher potential scenario would be capable of responding to grid events caused by a number of existing generation plants or similar capacities encountering issues that would
affect the national grid and would assist the TSOs to maintain reliable control of the overall network. Moreover, if additional assets identified during implementation of the proposed framework were included then much higher capacities and greater impact could be achieved. As demonstrated, if these larger capacity scenarios were implemented by only the LIEN 1 grouping, made up of sixty-nine of the largest pharmaceutical, chemical and healthcare companies in Ireland, then over 7.5 MW to 18.5 MW of flexible capacity could be achieved. An even larger impact could be achieved if this same scenario was implemented across the LIEN group, where almost 54 MW of flexible capacity could be provided in the highest potential scenario.

The financial performance is also demonstrated as a clear driving factor for the uptake of this concept within the industrial sector. Based on the initial low-risk benchmark capacities available from the case study, an individual participating site can expect to receive a base annual payment of between €3,000 and €7,000 for responding to each of the five DS3 system services before any scalars or performance bonuses are applied. Once the available scalars and payment multipliers are incorporated, sites offering capacities slightly larger than the low and high potential benchmarks can receive higher payments of between €11,000 and even up to €26,500 annually. This demonstration highlights the potential impact on an industrial site, where a representative site could expect to receive up to 14% of its annual electricity bill from these incentive payments. Additionally, based on the SNSP level scalar, even the lowest benchmark potential capacity could feasibly earn up to €21,500 and the largest scenario, AHU & Chiller High Potential, could receive up to €167,000 annually if each of their responses occurred when the grid SNSP level was above 70%. On top of these lucrative incentive payments, a site can also quantify and capture the amount of CO₂ they can eliminate through their DR participation. For an individual site providing 270 kW of flexible capacity in 2019, it would have been possible to eliminate almost 1.4 tonnes of CO₂ emissions to benefit the site itself and the national emission targets. These scenarios and scaling potentials offer an increasingly valuable resource to the TSOs as demonstrated by the impact highlighted and reliability they provide to the wider grid. They clearly benefit the continued incorporation of further RESs onto national electricity grids and assist the phase out of aging fossil fuel plants. These factors greatly assist national capabilities to achieve emission targets and have a considerable impact on the TSOs to maintain reliable control of the grid, particularly as the SNSP level continues to increase with more RESs making up the overall generation mix.
Chapter 6

Conclusions & Future Work

6.1 Summary of Research

The primary goal of this thesis and the research it presents, is to develop the body of knowledge, advance the provision of flexible capacity from the industrial sector and encourage further practical engagement in national DR programmes from this sector, by presenting a suitable framework that provides decision-support to potential industrial participants. This aim was systematically achieved throughout this thesis, following the defined ROs that represented the core elements of this research. Initially, a literature review critically assessing the current state of the art was conducted in Chapter 2, outlining the research area and detailing the integral concepts of the smart grid and industrial DR. This section provided an illustration of the predominant benefits, driving factors and barriers of these specific topics in addition to highlighting and expanding on a number of additional influential topics and terminologies related to these concepts. This section demonstrated that the main barriers to implementation and adoption of these topics were often perceived risk and a lack of clear understanding from potential participants and key stakeholders. This led to a detailed review of methodologies in Section 2.3, to evaluate previous examples of industry proven techniques and modelling approaches to overcome these barriers. The intention of this review was to provide a strong foundation from which to develop a defined framework to systematically identify and categorise the risk levels of including industrial assets in DR programmes.

The development and formalisation of the proposed framework is presented in Chapter 3, detailing each process, from the identification, categorisation to risk assessment step. This includes the outlining of the modelling approach and specific details required to create the risk-assessment modelling tool to evaluate operational risks of an industrial AHU participating in DR. This novel framework and its encompassed risk-assessment modelling tool are then applied on a relevant case study site in the following chapter, to demonstrate its applicability and fill the research gap of actual implementations in this sector and overcome the identified barrier of perceived risk and lack of clear understanding. This application in the industrial sector provides a clear indication that there are assets in this area suitable for participation in DR programmes at very low levels of risk. Furthermore, the outcome of this implementation
demonstrated useful flexible capacities from this site and provided an indication of the baseline, low-risk capabilities realistically achievable across the industrial sector.

The results of this study are further detailed in Chapter 5, highlighting the actual impact and potential available within this sector. The potential impact and risk levels of including an AHU serving an industrial office space in DR programmes are illustrated, including actual GFEs that occurred on the Irish electricity grid. These results provide encouragement to potential industrial participants and can help to inform future decisions in this area by outlining actual shutoff durations and specific capabilities in addition to demonstrating the risk-assessment modelling tool that can be utilised to assess other AHUs on the same or comparable industrial sites. Based on the research presented in this thesis, the additional potential impact and value to a participating site and the wider national grid can be clearly illustrated. The potential impact of scaling the participation capabilities up from a single site to a national scale are outlined, within the context of the Irish grid and industrial sector. Additional scenarios are presented that further highlight the financial and emission reduction benefits facilitated by this concept, compounding the predominant benefits previously identified Chapter 2. Overall, the fundamental goal of this thesis was presented in a few stages, as detailed in the following section, with the proposed framework and risk-assessment modelling tool providing a decision-support platform to encourage additional DR participation from the industrial sector and help contribute to the levels of flexible capacity required to maintain reliable control of the national electricity grid.

6.2 Conclusions in Respect of Research Objectives

In Chapter 1, four ROs were developed and outlined to guide the research and assist the successful realisation of the overarching goal of this thesis. These ROs are highlighted again in this section, in addition to how they were addressed by the research presented throughout this thesis.

RO1. Assess and critically appraise the predominant benefits, driving factors and barriers to industrial engagement and participation in national electricity grids.

During the literature review conducted in Chapter 2, the predominant benefits, driving factors and barriers to the concepts of smart grid and industrial demand response were presented, as two of the key concepts in the area of participation in national electricity grids. These specific aspects for each topic were presented in detail and summarised in Tables 3 and 6 of this thesis.
The predominant benefits of these concepts were found to be improved grid control and reliability, facilitation of higher levels of RESs and DERs, the maximisation of existing assets and dual cost and emission reductions in addition to new and more lucrative revenue streams. The key barriers to overcome were found to be a lack of clear understanding and perceived risk, in addition to believed cost, lack of impact and value generation, cyber security threats and perceived need for behavioural changes and acceptance of external influences. The assessment of these barriers led to the identification of the need for a defined framework to mitigate and reduce this perceived risk and lack of clarity, which would help to uncover additional potential and provide further benefits, as outlined, to the participants and national electricity grid.

**RO2.** Investigate and formalise a prescriptive framework to advance industrial participation in DR schemes and provide decision support to inform and encourage additional industrial participants.

The investigation of influential methodologies and approaches in Chapter 2 highlighted a number of key aspects in this area, most notably the DOE methodology, ISO 31000 risk assessment techniques and criticality ranking approaches to design and create a prescriptive risk assessment framework suitable for the industrial sector. The aim of this framework is to present a defined systematic guide for industrial participants to identify suitable assets on their site to participate in DR programmes, thus providing clarity and reducing any lack of understanding in this area. This proposed framework, presented in Chapter 3 and implemented on a representative industrial site in Chapter 4, can help to provide decision support to potential participants who follow each process step. Allowing them to identify low risk and appropriate industrial assets for DR participation to benefit themselves and the wider electricity grid. The value of this has been demonstrated, based on the flexible capacities available on the case study site that could realistically be expected from other industrial sites. Further encouragement can be found for other potential participants through the formation of the asset register, which can continually be referred to as a current asset register of suitable DR assets, providing additional clarity and sustainability for this concept.

**RO3.** Develop a suitable risk-assessment modelling tool to evaluate and demonstrate elements that influence the operational risk of a suitable industrial asset participating in DR to minimise the perceived risk and encourage further participation in the industrial sector.
Following the review of relevant literature and previous examples in Chapter 2, GB modelling and the RC approach were found to be commonly applied and effective methods to model internal air temperature within office spaces served by industrial AHUs. The 1R1C approach specifically was found to be suitable, where modularity and computational efficiency are key parameters, making this applicable for the development of a risk assessment modelling tool to evaluate and demonstrate any potential operational risk of an AHU participating in DR. This particular risk-assessment modelling tool was presented, detailing its development and the calibration process, based on recognised approaches like the Morris method to ensure confidence in its outputs. To demonstrate the suitability of this risk-assessment modelling tool, it was applied to a representative case study industrial site, on which AHUs were identified as being suitable for DR. This application included the classification of building thermal characteristics and collection of empirical data for calibration using recognised statistical accuracy metrics. This resulted in a modelling tool capable of predicting internal air temperatures, with accuracy metrics of 0.3°C RMSE, an $R^2$ of close to 0.5, a total of 0.2°C MAE, only 0.22% MBE and a final PC of 0.93, which help to provide further clarity and minimise any doubt in its outputs. The development and implementation of this tool was invaluable to evaluate and demonstrate any operational risk of the selected AHU participating in DR, clearly illustrating the actual effects and minimising the perceived risk associated with its inclusion in flexible capacity portfolios. This tool can help to reduce the perceived risk and demonstrate the performance capabilities of this AHU and other similar applications in addition to the other outputs and valuables insights this demonstration has provided to encourage further low-risk DR participation in the industrial sector.

**RO4.** Quantify and highlight the potential benefits of selected industrial assets deemed as low risk being incorporated into DR programmes and illustrate their potential impact on the Irish national electricity grid.

The results, impact and discussion presented in Chapter 5 highlight the considerable benefits achievable through widespread engagement in DR across the Irish industrial sector. Following the evaluation and risk assessment of general and actual grid events in Section 5.2, it is clear that AHUs in the industrial sector can generally be defined as low-risk assets for DR participation. The scaling potential of these assets is clear, with between 7 MW and 15 MW of flexible capacity potentially available from the LIEN 2 group, representing the largest companies in the Irish industrial sector. Moreover, approximately 15.5 MW to 18.5 MW of flexible capacity could be made available to the TSO, if industrial AHUs with additional
capacity from a participating chiller were included from the LIEN 1 group, which is made up of only 69 companies closely related to the case study site on which this framework was applied. The grid reliability and emission reduction capabilities on a site and wider grid level provide considerable benefits to all stakeholders, which may lead to policy makers increasing efforts to incentivise DR participation on the national grid even further. Moreover, the potential financial performance and incentive payment benefits achievable on a site can help to encourage additional participation from the industrial sector. Based on current figures, a single participating industrial site offering only 270 kW of flexible capacity could expect to receive up to €167,336 annually, if each of their response events occurred when the SNSP was above 70%. This quantified financial performance may help to encourage additional participation from the industrial sector and assist the provision of the required grid flexibility allowing the TSOs to maintain reliable control of the national electricity grid.

6.3 Critical Appraisal of Limitations of Research Undertaken

As the research presented in this thesis is focused in the industrial sector, it is important that the framework, risk-assessment modelling tool and overall approach be understood in this context. It is especially pertinent that the modelling approach, focused on industrial office spaces and electricity market participation as detailed throughout this thesis, and its resultant findings, be understood in the context of the industrial sector, these particular buildings and the purpose being evaluated. Overall, it is the opinion of the author that this research contributes to the advancement of this research area and may help to encourage additional industrial participation in DR within national electricity grids, thus, helping to close the identified knowledge gap highlighted in previous sections. However, it is also important to highlight some of the assumptions and possible limitations of the research undertaken. The following sections outline these potential aspects under the headings of three of the main contributions presented in this thesis.

6.3.1 Framework

A key aspect to ensure the success of this concept and an assumption from the outset is that a potential industrial participant is willing and committed to participating in DR from the beginning and throughout their engagement in this process and implementation of this framework. This is important to achieve the required levels of stakeholder engagement, particularly during Steps 1, 3 and 4 of the framework. As ensuring SMEs from each of the teams and areas are made available to participate and top-level management representatives
are engaged is vital to maintain progress and ensure decisions and actions are suitably progressed. Another aspect mentioned in previous sections is the potential subjectivity and element of human influence in the asset categorisation process, which may be seen as a potential limitation of this framework. This is mitigated through the semi-structured and silent brainstorming applied during this decision-making process, including the quantitative affinity diagram process that helps to reduce bias. However, this may be reduced even further by incorporating additional reflexivity into the process, particularly following additional case studies and implementations. This would allow further critical analysis to be conducted before, during and after this step, based on previous experience and evidence-based examples.

Furthermore, the iterative framework design and sustainable asset register for flexible assets that it produces, allows the outputs to be updated continually. Therefore, if the initially selected assets are found to be too conservative or risk averse, additional assets can be included in the response portfolio to increase the flexible capacity presented or highlight areas for change to allow this to happen. This element however, may be seen as a limitation of this framework during initial implementation or at an early phase, before other case studies or successful iterations have been completed which would increase acceptance and levels of confidence in this concept.

### 6.3.2 Risk-Assessment Modelling Tool

Another potential limitation of this study in relation to the risk assessment modelling tool mentioned in previous sections is that internal air temperature is taken as the main indicator of performance and risk levels within the internal space. Although this was selected as it most simply illustrates the effect and any potential risks to the zone and is commonly available on industrial site’s BMSs to maximise its suitability and general applicability, it may not be the most comprehensive indicator of actual thermal comfort within the space. Including additional input data like CO₂ or humidity readings would help to increase the accuracy of overall internal air quality prediction within the space and as this is not currently included in the modelling approach this may be seen as a limitation of this research. Furthermore, including this data would allow the rate at which CO₂ levels increase within the room during a shutoff and decrease in the time thereafter to be evaluated, which may add value to the user particularly highlighted during the COVID-19 restrictions and how these impacted AHU operations. This research is also focused on CAV AHU systems as the initial basis for the model, which were found on numerous case study sites and are very common in the industrial sector, particularly in older existing buildings [258]. However this may been seen as a limitation as the research and
modelling approach would need to be extended further beyond the scope of this study to incorporate alternative HVAC system types and therefore capture every possible system configuration found in this sector. Additional variables or calculations may be required for more advanced systems, where complex setups with varying airflow systems, heat recovery strategies or refrigeration cycles are required. Finally, this thesis only presents the application of this AHU risk-assessment modelling tool although other asset specific tools could also be implemented as part of the overall framework. This may be seen as a limitation if other assets identified as suitable for DR required further modelling analysis and evaluation.

6.3.3 Results & Impact

A further potential limitation of this research worth noting is in relation to the impact and possible scaling scenarios previously discussed. The main assumption that these scaling scenarios are based upon is that each participant within these groupings would engage in the process, however in reality this may not be the case. These scenarios are designed to give a general overview and broad-stroke depiction of the scaling potential of this concept. To increase the accuracy and integrity of these scenarios, a more comprehensive and detailed study would need to be conducted, addressing each company or building within the LIEN or the wider industrial sector to capture each individual’s preferences and site specifications. Therefore, the groupings and scaling scenarios in their current form only offer indicative values, which may be viewed as a limitation of this study. Additionally, further performance and detailed cost analysis of the potential financial gains and incentive payments achievable may be required to present these findings even more clearly. The current quantifications assume the site is available and could respond to each potential GFE, which in reality may not be practical or feasible. This would help to outline the benefits of participation further and possibly outline a defined minimum capacity requirement to ensure cost effectiveness for the participant, which may help to encourage more engagement in DR from the industrial sector. The supplementary cost and payment details would benefit decision makers in this area, in addition to highlighting the value of participation further, which would demonstrate and strengthen the long-term sustainability of this concept.

6.4 Recommendations for Future Research

This thesis presents research and novel contributions that are intended to develop the body of knowledge and advance the practical engagement and participation of the industrial sector in
DR programmes within national electricity grids. The following topics logically follow as the natural extension to this work, based on the research and impact presented in this thesis:

- As outlined in previous sections, reducing the potential subjectivity within the categorisation process represents an avenue for future work stemming from this research. Further investigation into assets successfully incorporated into DR programmes, similarly to the AHUs investigated in this research, would help to build up a portfolio of suitable assets and provide clear examples of each of the categorisation levels. This could then be utilised as a benchmarking tool or appendix from which to make decisions on new assets based on a rigorous existing body of knowledge to build further confidence in their selection.

- Additional analysis and potential trials of suitable assets would also be a logical next step to advance the research presented in this thesis. Evaluating assets like industrial chillers and compressors with potential buffer capacity, as well as other AHUs to determine their response capabilities would provide valuable information for potential industrial DR participants. A detailed investigation into the DR capabilities of variable speed fans and drives would also add value, particularly if they could be utilised to provide flexible capacities without having to shut the asset off entirely. The response times and performance validation of these potential strategies would require further investigation, to determine whether they would be suitable for DR and if so, which specific system services they could participate in based on defined capabilities.

- There are also several research opportunities based on the modelling tool presented to further develop this aspect and further enhance its outputs. One element of future work that may add value would be to conduct trials or further occupant surveys to more accurately quantify actual perceived temperature drifts and incorporate these practical findings into the model outputs. Variables like occupant perception and expected temperature could present interesting findings, with lighter clothing levels in summer or warmer occupant clothing levels and hot drinks during the colder months potentially influencing the actual thermal sensation and allowable limits in the office spaces during these times. Furthermore, based on existing studies previously discussed [221], the temperature drift limits outlined in ASHRAE 55 may be overly conservative. Based on the results of trials or other data collection methods, the model could be updated with less stringent but still appropriate limits, which would still maintain suitable conditions within the zone but allow for higher levels of flexibility and DR performance.
Furthermore, based on the modularity of the modelling approach and selected software, additional features and data sources could be included to supplement the existing model outputs. For example, the inclusion of existing or new CO\textsubscript{2} sensors within the zone would allow this data to be included in the risk assessment. This future work would allow for evaluation of the CO\textsubscript{2} levels during DR events under ventilation criteria defined by the ASHRAE 62.1 standard or other COVID-19 or site-specific requirements. Incorporating this additional factor and potential limits into the model would provide further valuable insights and ensure a more comprehensive risk assessment is conducted.

Extending the scenario analysis further may also benefit policy decision-making, particularly in relation to catching up to or equalling countries with more advanced electricity grids. For Ireland to reach its emission reduction targets it will need to learn from European TSOs and other advanced examples like the Californian electricity market. To investigate the potential available further, this framework could be applied across the Irish industrial sector or to evaluate the scenarios presented in this thesis more rigorously, a probability analysis could be conducted. A Monte Carlo probabilistic analysis may be suitable to estimate the flexible capacities available from individual companies to analyse specific aspects in more detail. Utilising these scaling scenarios would help to quantify some of the figures previously unknown, assisting more evidence-based decisions to be made. Moreover, the regional grid analysis may inform planning decisions and help to mitigate congestion issues on the transmission network. Although currently these are not a major issue in Ireland, as the levels of DERs and local generation increases this may become more relevant, similarly to the locational marginal pricing and regional electricity grid requirements commonplace on the Californian electricity network.

A detailed cost analysis and financial performance study would also add further value in relation to encouraging additional engagement from the industrial sector in DR programmes and would be a natural progression from the results presented in this thesis. Additional detailing on the cost savings and incentive payments actually achievable would provide valuable information for new and existing DR participants. On a wider scale, this information could inform government and policy makers’ decisions on the formation of new and revision of existing incentive scheme structures to offer the best value and sustainability of programmes in this area.
References


[16] Department of the Environment Climate and Communications and Government of


[47] Sustainable Energy Authority of Ireland, “Large Industry Energy Network (LIEN),”
References


References


References


References


[182] F. Amara, K. Agbossou, A. Cardenas, Y. Dubé, and S. Kelouwani, “Comparison and


References


Appendix A

Figure A1. Screenshot of model code in Jupyter Notebooks, to initialise code, read in external data files and set both variables and initial values.
Figure A2. Screenshot of model code in Jupyter Notebooks, to simulate internal air temperature and capture any impact of a DR event.
Table A1. Overview of events where the grid frequency dropped below 49.75Hz during the years 2019 and 2020.

<table>
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<tr>
<th>#</th>
<th>Date</th>
<th>Start Time</th>
<th>Duration [s]</th>
<th>Trigger</th>
<th>Frequency [Hz]</th>
<th>Frequency Range [Hz]</th>
<th>Frequency Event</th>
<th>AHU ON</th>
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Figure A3. Bubble charts of 2019 grid frequency data, illustrating (a) each time the frequency dropped below 49.7 Hz and (b) each time the grid frequency fell below 49.75 Hz. Events in each month are shown in different shades of the months colour, the trigger frequency determines the bubble’s Y-axis location and the duration that the frequency was below the threshold, in seconds, determines the bubble size in each case.
Figure A4. Bubble charts of 2020 grid frequency data, illustrating (a) each time the frequency dropped below 49.7Hz and (b) each time the grid frequency fell below 49.75Hz. Events in each month are shown in different shades of the month’s colour, the trigger frequency determines the bubble’s Y-axis location and the duration that the frequency was below the threshold, in seconds, determines the bubble size in each case.
Figure A5. Overview of measured CO₂ levels within the case study internal office space during normal AHU operating schedule, demonstrating distance from the ISO/TR17772-2 limit of acceptability.