How to characterize flexibility requirements of highly renewable energy systems over multiple timescales

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Abstract

This thesis addresses the question: *Can we characterize requirements for flexibility over different timescales in electricity systems dominated by solar and wind power?* Storage and flexibility play an increasingly important role, but there is great uncertainty about amounts of flexibility needed and how they depend on generation mix and demand, including electrification of heating and transportation. Furthermore, to inform investment and planning, it is valuable to characterize the timescales over which flexibility will be needed, as different resources can be used to shift energy over different time horizons.

To address this problem, the analysis uses the novel application of three methods to disaggregate overall flexibility requirements into short-, medium-, and long-term requirements, without relying on assumptions about technology parameters or costs. These methods are illustrated using the case of Great Britain and results are used to draw insights into GB flexibility needs under future scenarios.

Flexibility is required over multiple timescales, from less than hourly to inter-seasonal or longer. Overcapacity of renewables provides value in terms of avoided storage costs, particularly displacing requirements for the longest duration storage, though generation capacity beyond 120% of demand yields diminishing marginal returns. Heating electrification has a larger impact than EVs, though flexible heating can partially offset additional power capacity needs.

In all cases, the capacity required to shift energy by up to a day was on the order of 1 TWh; this could account for over half of all energy shifted depending on flexible resource operation. Electricity systems with at least 80% of energy from solar and wind require 3-150 TWh to shift energy by weeks or longer. The required capacity to shift energy by more than one year could potentially be avoided using renewables overcapacity, dispatchable generation, or interconnectors.

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1

Introduction

This thesis addresses the question:

Can we characterize the needs for flexibility over different timescales in future electricity systems dominated by solar and wind power?

The thesis explores what is required for system flexibility and storage over different timescales and shows how short- and long-term needs vary with generation mix and electricity demand.

1.1 Context

The main research question must be answered to enable the decarbonization of the electricity system in line with increasing urgency to mitigate climate change [1]. To achieve decarbonization, the electricity sector needs to incorporate much more variable renewable generation. Meeting electricity demand in power systems dominated by variable renewable energy sources requires significant amounts of flexibility to ensure secure and resilient service provision [2].

Many different flexibility options will be needed to shift energy and power in time (e.g. storage, demand response) and across space (e.g. interconnections). Different types of flexibility assets will be used for to shift energy over seconds, minutes, hours, days, weeks, seasons, and even between years. Therefore, to adequately plan as the system evolves, it is important to understand the requirements for flexibility over different timescales under a variety of future scenarios. This will enable identifying least regret options for investment in system flexibility which make sense under most potential future scenarios.

1.1.1 Energy transition

Transitioning to low-carbon based energy systems is a crucial part of mitigating further climate change and providing affordable, reliable energy to the world's population. Technological advancement, strategic public and private policies, and changing social attitudes have contributed to some climate change mitigation, including significant investment in renewable energy [3]. Incorporating larger shares of variable renewable energy sources into energy networks introduces new challenges for balancing demand and supply of energy in real time [4, 5, 6]. These challenges will require additional infrastructure investment, further development of new and promising technologies, evolution of social practices, and appropriate policies to incentivize and regulate these changes [7, 8, 6, 9, 10, 11].

It will be important to better understand which flexibility sources can ensure both system stability and affordable access to electricity under different potential decarbonization strategies. Given the uncertainty about future technologies and infrastructure, climate change induced weather patterns, and electricity demand, there is a need to investigate how flexible resource requirements, demand side flexibility options, and viable flexible resource portfolios may vary with these assumptions.

Shifts in generation

Decarbonizing the energy system involves switching to less polluting fuels, possibly capturing greenhouse gas emissions, and reducing demand through efficiency gains and shifting social practices [4, 6]. The transition toward low-carbon energy sources has primarily taken place in the electricity supply sector, both worldwide [3] and in the UK specifically [12]. For electricity generation, this transition will be driven in part by switching to low-carbon energy sources, including wind, solar, and nuclear power generation [13, 14, 15]. If electricity is generated using more low-carbon sources, electrification may facilitate decarbonization of heat and transportation sectors [8, 14, 15].

A growing share of electricity is generated by renewable energy sources [3], including variable solar, wind, wave and tidal power, dispatchable biomass, geothermal, and hydropower. The variability and uncertainty of wind and solar power are some of the barriers to meeting all electricity demand through renewable sources [4, 7, 8, 6]. Continuing to scale up the share of renewables in the energy mix will require solutions to meet power demand even when the sun is not shining and the wind is not blowing, which may become increasingly important given climate change.

Dispatchable fossil fuels continue to dominate the energy supply sector globally, despite significant shifts toward less polluting fuels [3]. Switching from coal to natural gas, which emits fewer greenhouse gases and air particulates per unit of energy, has contributed to reductions in greenhouse gas emissions and improvements in air quality [12]. Nuclear power stations can provide reliable low-carbon electricity, though they cannot easily and quickly ramp up or down to deal with changing demand or to compensate for loss of supply from another generator [7, 16], although innovation in small scale modular nuclear reactors is improving and making these increasing promising for some future generation that is more flexible than traditional nuclear power.

Shifts in demand

Electricity demand is also changing. Globally, increasing access to electricity has increasing demand significantly and will continue to do so [3]. In the UK, baseload electricity demand has been decreasing for the past five years due to a combination of energy efficiency measures and outsourcing of energy intensive industries to other countries [2].

However, trends of increasing digitalization and electrification of vehicles mean electricity demand is likely to increase again in the coming decade [2]. If there is widespread electrification of heating, electricity demand will increase significantly especially in winter evenings, already the peak times for power usage [2].

These trends could lead not only to increases in electricity demand, but to shifts in the patterns of demand, with different times of peak demand and different needs for system balancing.

Electricity system operation

System operators must balance electricity use and generation within prescribed bands in real time. To maintain system stability, they call on various resources, which together provide the required power, at the appropriate ramp rates, and for the necessary durations.

Currently, flexibility to respond to changes in demand or unexpected supply failures comes from conventional dispatchable power generation, interruptible loads, demand side management (DSM), storage, interconnectors, curtailment, and behind-the-meter back-up generation [7, 8, 6, 15]. These grid resources may be used for frequency regulation and for energy arbitrage to use lower-cost or less-polluting electricity [17].

Different markets deal with these services in different ways and often classify them by the time for response and amount of power provided [18]. These could include markets for responses within seconds, within minutes, within half an hour, or day-ahead markets, and markets to provide power further into the future.

1.1.2 Need for additional electricity system flexibility

Future electricity systems with energy mixes dominated by variable renewable sources and inflexible nuclear power will lead to significant system balancing challenges, increasing the need for reserves and grid services [4, 7, 6, 19, 17]. The ramping, power capacity, and energy capacity requirements may be different for more inflexible supply profiles dominated by variable and uncertain renewable power. Additionally, running coal or gas generators partially loaded, to provide power in times of low variable renewable generation, is expensive and still polluting, particularly considering start up durations and minimum stable generation limits of these plants, and can lead to reduced efficiency, reduced life span, and higher maintenance costs [20, 7].

New flexibility resources will be required to maintain stability and achieve access to affordable, low-carbon electricity [8, 6, 19, 10]. How much of each resource and when it is required depends on demand and supply profiles [7, 6], which are highly variable and quite uncertain [4, 8, 14, 15]. In the face of such uncertainty, many possible future scenarios have been developed to capture the variety of potential energy mixes, technological developments, changes to demand patterns, and pathways for investment [15, 4, 14, 13].

For example, the National Grid Future Energy Scenarios scenarios outline four potential futures for Great Britain's electricity system, which include different assumptions about energy mix and demand profiles [2]. Even among other studies which focus on 100% renewable energy mixes, there is considerable variation in assumptions about energy mixes, demand profiles, and available flexible resources [21].

1.1.3 Need to understand flexibility requirements

Although several studies investigate the need for storage and flexibility in highly renewable power systems, few of these focus on understanding the system requirements, and they do not break these requirements into the timescales over which flexibility is needed.

Better understanding these flexibility requirements, including timescales over which energy must be shifted, can yield insights about which resources may be suitable to meet these flexibility needs and could inform decisions about investment pathways for a cleaner energy system. To this end, it will be critical to understand not only total system requirements, but also the differences between short-term and long-term requirements and how these vary under potential future scenarios. For example, storage assets with large self-discharge may be suitable on the order of hours or days, but inappropriate for shifting energy over longer timeframes. Selecting correct technologies to store not only the appropriate magnitudes of energy, but over the correct timescales, can dramatically alter system design and operation with huge economic and emissions repercussions.

Few studies estimate the timescales required for energy shifting or amounts of time for which energy would need to be stored. Most approaches assess adequacy of portfolios with different types of storage resources, analyzing how much demand is met or how much variable renewable energy is curtailed [22, 23, 24], rather than the system requirements, although one approach uses monthly data to make a case for interseasonal shifting [25].

Existing analyses which integrate multiple storage types and timescales [26, 27, 28] or which explicitly address long-term or interseasonal storage [27, 29, 24, 30, 28, 31] produce capacity estimates which rely on assumptions about technology parameters and costs. Therefore, while these papers show that long-term storage could have a role to play in those defined scenarios, they do not address whether or under which conditions a power system might require long-term energy shifting.

Given the uncertainty about future energy system configurations, it is important to investigate how these storage requirements depend on the generation mix [32], rather than assess the optimal strategy for a particular set of conditions. Additionally, the costs of renewable generation technologies, storage technologies, and other flexible resources have been rapidly falling [33, 34, 35, 36]. Therefore, the cost-minimizing combination of generation and storage could change based on how these technology costs develop and fall relative to each other over time and there is a need to better understand investment strategies for a wide range of potential cost trajectories.

There is a need to characterize power system flexibility requirements under different low-carbon energy mixes and demand conditions and to investigate how the needs for flexibility over different timescales varies in these systems. To ensure that the results characterize the requirements of the system and do not depend on assumptions about technologies or costs, there is a need to do the analysis in a way which is agnostic to the types of assets used to meet the need for flexibility.

This thesis aims to address these gaps by quantifying the the need to shift energy through time in wind and solar dominated systems, and therefore to quantify the flexibility requirements over different timescales, while being agnostic to the technologies which would provide that flexibility.

1.2 Scope

To address the research question, it can be broken into the following research sub-questions. Each of these topics is answered in the following chapters of this thesis.

1. How can flexibility requirements over different timescales be characterized? (Chapter 3)
2. What are the flexibility requirements of a future renewable dominated electricity system in Great Britain? (Chapter 4)
3. How does the generation mix affect flexibility requirements, using the case study of Great Britain? (Chapter 5)
4. How would potentially significant shifts in demand, for example due to electrification of heating and transportation, affect flexibility requirements, using the case study of Great Britain? (Chapter 6)

To ensure a consistent narrative arc and results which could yield insight, decisions were made to bound the scope of this work. These decisions are discussed in the following sections.

1.2.1 System flexibility

The system refers to the electricity system, not the entire energy system. Therefore system flexibility requirements refers to the flexibility required in the electricity system only.

This thesis focuses on the temporal dimension of flexibility – the need to shift energy and power through time to meet demand, or the need to shift demand in time to better align with inflexible generation.

The spatial dimension of flexibility is not considered in the flexibility requirements of this work. Spatial flexibility – shifting energy and power across space using transmission and distributions networks and interconnectors – via enhanced transmission networks and increasing use of interconnectors will play an important role in existing and future power systems. However, in this thesis we use a copper plate assumption[1] for the system to consider that the spatial flexibility has been used to the maximum. Therefore the remaining needs for flexibility cannot be met by further spatial flexibility within the system, and the flexibility requirements identified must be temporal flexibility requirements.

However, the locations of generation and demand, the networks constraints, and also the locations of storage asset are important considerations for future system planning. For example, while this analysis will suggest minimum capacity requirements, the load factors of wind (both onshore and offshore) and solar generation vary considerably by location, so additional capacity or demand reduction in one location may be worth more than in another location. However, network constraints mean that additional capacity in the areas with highest load factor might not be the system optimal locations if that additional generation would just be curtailed. These and other spatial considerations to investigate the robustness of the results and conclusions in this work will be an important area of future work.

To estimate flexibility required, this thesis estimates the minimum capacity of flexibility resources which could meet 100% of demand. A real-world system may need greater capacity than this as reserves to ensure resilience, or it may require less by setting the reliability target slightly lower[2].

1.2.2 Scenarios

This thesis aims to understand the flexibility requirements of extreme scenarios, in potential electricity systems without fossil fuels and where generation is not flexible or dispatchable to meet demand. Therefore, the only electricity generation sources considered in most analyses are wind (both on-shore and off-shore), solar

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[1] We ignore network constraints.

[2] One could argue that not meeting that demand is itself a form of system flexibility.

photovoltaic (PV), and traditional nuclear power. Most of the analysis uses scenarios where all electricity is supplied by wind and solar generation. The analysis of these extreme scenarios is useful for insights into system potential and limits, but not an expectation or recommendation for future power systems.

1.2.3 Geographical context

The methods developed could be applied to any location to characterize the need for flexibility over different timescales under different future scenarios. However, the specific results of flexibility requirements, and how they vary with generation mix or demand patterns, are highly location specific.

This thesis applies the methods and focuses analysis on the context of Great Britain (GB). This choice was made primarily based on the availability of enough years of data at the temporal resolution required for all relevant variables.

1.3 Structure of thesis

The following chapters are structured as follows. To identify gaps in the literature, Chapter 2 summarizes related work. To answer sub-question 1 and develop methods used in the remainder of the thesis, Chapter 3 describes the methods developed to characterize the need for temporal flexibility in energy system, including approaches to estimate overall flexibility requirements and to disaggregate these requirements over different timescales. To illustrate these methods, Chapter 4 applies these methods to the case of Great Britain with a fully renewable energy system, to illustrate how the methods could be applied at scale and to understand a potential scenario in depth, answering sub-question 2. To address sub-question 3, Chapter 5 investigates how these flexibility requirements depend on the generation mix, using the case of Great Britain to understand how flexibility needs vary with different penetrations of solar, wind, and nuclear generation. Chapter 6 addresses sub-question 4 by investigating how the flexibility requirements depend on demand, to understand how adding demand from electric vehicles and electric heating with varying degrees of flexibility could affect remaining system flexibility needs in GB. Chapter 7 concludes by drawing bringing together the insights from the previous chapters and showing how these address the overarching question of how can we characterize flexibility requirements of highly renewable power systems over multiple timescales.

2

Literature Review

This chapter reviews some of the relevant literature and identifies the gaps that this thesis aims to fill. In particular, the following sections discuss flexibility in electricity systems, approaches to modelling flexibility, and sizing storage and other assets. They highlight relevant work that has been done and then identify four gaps that the rest of this thesis aims to address.

2.1 Flexibility in electricity systems

To be able to characterize flexibility over multiple timescales, it is first helpful to understand where flexibility comes from and some of the different definitions and metrics which are already used for flexibility. The next sections look at existing sources of flexibility in power systems, definitions, and metrics.

2.1.1 Flexibility definitions

The Oxford English Dictionary defines flexibility as "capacity for ready adaptation to various purposes or conditions" [37]. There is currently no established definition of flexibility specifically in power systems, nor a widely-used standard in academia, policy, or industry. We organize existing definitions based on their context, perspectives, and included criteria.

Context

Electricity system flexibility is an area of active research in engineering, economics, and policy, which has led to both technical and market-oriented definitions [18, 9]. Historically, power system flexibility was primarily a concern for infrastructure and investment planning and limited to supply side generators [38, 39] and network configurations [40].

More recent definitions have not limited the flexibility sources and advances in monitoring, communication, and control technologies have enabled demand side management and energy storage to contribute to system flexibility. One widely cited definition is “the ability of a system to deploy its resources to respond to changes in net load” [41], where net load is the residual demand unmet by variable electricity generation. Although some define flexibility specifically in the context of variable renewables [20, 41, 42], previous studies have addressed flexibility requirements arising from uncertainty in fuel prices [39] and from unforeseen equipment failure [38, 40].

Market-oriented literature has defined power system flexibility either as a characteristic of a system, including its resources and market structure [43, 44] or as a good which could be procured, bought, sold, and traded [17]. The commodity procured may be power, energy, or the availability to change power output (whether or not any services are provided). Moving forward, we limit the scope to technical definitions and criteria.

Approach

Definitions of electricity system flexibility take either a top down or bottom up perspective. Bottom up approaches [38, 41, 45, 46, 47, 42] focus on how flexible a particular system or resource is (flexibility available). Flexibility available gives a sense of how much a system could change from its current state and therefore the limits to conditions that the system could cope with.

Top down approaches [20, 48, 47, 49, 9] define how flexible a system would need to be under particular conditions (flexibility required). These represent two approaches to the same problem, as successful systems have enough flexibility available to meet flexibility requirements under all likely conditions, considering physical, economic, environmental, political, and social constraints.

This thesis uses the top-down approach of estimating flexibility required.

Time dependence

Approaches to defining electricity system flexibility can be divided by whether or not flexibility varies with time. Time-independent definitions of flexibility [38, 45, 42] describe a characteristic, feature, or limit which does not depend on how the system or resource is operated or on external conditions. Using a time-independent definition of flexibility can facilitate comparisons between systems with different configurations or resource portfolios and are appropriate for long-term investment and planning models.

Time-dependent definitions [50, 41, 51, 52, 47, 43, 53, 54, 55] describe how flexible the system or resource is at a particular time, depending on changes to operation or external conditions. Time-dependent definitions are suitable for operational scheduling and market models because a system's ability to respond to changes is influenced by how it is operated.

Technical perspective

Some definitions have power-centric [47, 43], energy-centric [56, 57], or ramping-centric [58, 55] perspectives of electricity system flexibility.

Ramping-centric flexibility definitions include "the ability to sustain ramping for a given duration" [58] and "potential to change power at a certain rate" [55]. Considering ramping is important because physical ramping constraints can limit ability to meet demand even in systems which have enough power capacity and energy to deploy. However, focusing how easily or quickly a system or resource could change its state does not yield insight into the magnitude of power and energy which could be supplied at that rate. Definitions such as "potential for capacity to be deployed within a certain timeframe" [46] address this by considering both ramping and power perspectives.

Power-centric definitions, such as "power capacity this resource could potentially deploy" [47] or "a power adjustment sustained at a given moment for a given duration from a specific location within the network" [43], align with the view that flexibility comes from the resources for system operators and markets to balance power generation and use in real time. However, power-centric perspectives neglect ramping and energy constraints which influence whether a resource is able to provide the power capacity within the timeframe and for the duration needed.

An energy-centric perspective may be helpful in systems which rely on storage and demand side resources, where flexibility available is limited by finite energy capacity and depends on how resources are used. For example, operating reserves can be described as "flexible deployable energy, rather than flexible deployable power" [56].

Although each of these perspectives has advantages, flexibility depends on power, energy, and ramping abilities. When examining system requirements, it is important to consider the capacity required of flexible resources in terms of these multiple dimensions, rather than focusing on a single dimension.

Additional criteria

Several definitions recognize that physical criteria are insufficient because the ability to be flexible depends also on costs [45, 53], location [52, 43], and quality of service provided by the electricity [59, 57]. Although these factors have been included in flexibility definitions by the authors, they may be better suited as potential indicators and metrics of flexibility.

2.1.2 Flexibility metrics

Flexibility in electricity systems has been quantified using technical characteristics, economic costs and benefits, and custom flexibility indices. According to Lannoye et al. [41], good flexibility metrics quantify the ability to respond to short-term changes (e.g. load shifts, generation outages, variable generation), minimize data and computation requirements, and are independent of reserve definitions. However, according to Menemenlis et al. [50], a "single, general-purpose measure of flexibility does not make sense". This section reviews some of the technical, economic, and index-based metrics in the literature.

Technical metrics

Technical metrics are good flexibility indicators because they are standard metrics in all power systems and they yield insight into physical limits and constraints, though overlaps or interactions between resources must be considered. However, physical resource metrics are insufficient to capture all factors which contribute to system flexibility. Whether or not technical flexibility metrics are sufficient, depends on the question being addressed and how the resulting measurements are being used.

A common bottom-up approach to system flexibility, which estimates the flexibility available, uses the sum of the flexibility of all of the resources in the system [38, 45, 60, 42]. A resource's maximum power capacity, minimum stable generation, ramp up and ramp down rates, start up and shut down durations, minimum up and down durations demonstrate how flexible the resource is [45, 42]. In addition, a resource's location, temporal availability, power direction (uni- or bi-directional), and predictability influence its ability to contribute to system flexibility [43]. Another bottom up measure of a system's flexibility is its physical resource capacity, including interconnections, pumped hydropower, combined heat and power plants, and gas turbines [61].

Alternatively, power systems can be evaluated based on their flexibility needs under changed conditions. Maximum and minimum residual demand [9], demand not met (insufficient ramping resource [41] or expected energy not served [47]), energy surplus (curtailed [20, 47, 62] or stored [9]), maximum and minimum ramp rates required, and durations and frequency of supply and demand mismatches can provide insight into the types and amounts of flexibility required. Additionally, risk tolerance for failure influences flexibility needed by a system [63]. These indicators give a sense of the scale of the flexibility challenge and the consequences if it is not addressed properly.

Economic metrics

Because of the implications for infrastructure investment and for energy markets, flexibility has been quantified by its economic costs and benefits [38, 39, 60, 5, 19]. Some market-oriented approaches use price elasticity of electricity demand, the amount of money one would pay to use the next marginal unit of power or be paid to not use the electricity, as a measure of demand side flexibility [64, 17].

These metrics are appealing for several reasons, particularly given the interdisciplinary nature of energy systems research. First, using a single dimension enables comparisons between different resources or systems. Second, cost is widely understood across sectors and industries. Third, energy systems are inherently linked with energy markets, so cost metrics facilitate deeper collaboration and integration of research.

However, relying on costs and benefits obscures physical differences between resource properties, which influence the types of flexibility they could provide. Additionally, the assumptions, approximations, and tradeoffs from assigning value to non-economic costs and benefits are not immediately obvious to the metric user.

Flexibility Indices

Several researchers have created indices and composite metrics to quantify system flexibility.

The grid edge index, developed by Zachau Walker et al., assesses different countries' need for and readiness for grid edge solutions, with the need for flexibility being major driver of the need for grid edge solutions [65]. While this index does focus on the need for flexibility, the scores of each country are relative. The index is therefore useful for identifying potential new markets to deploy flexible resources or which others countries to look into their policies which have improved system readiness for deploying flexible resources. However, each country's score does not shed light into particular technical requirements and how one might meet those requirements.

Some system metrics indicate the range of possible conditions within which a system can meet all of its needs. The “largest variation range of uncertainty” [63] captures the lower and upper bounds of uncertainty that a system can cope with. Another flexibility index indicates the range of possible operational states by plotting energy, ramping, and economic constraints on a three-dimensional axis and defining a flexibility index as the ratio of volumes bounded by operating possibilities and physical constraints [50]. In another study, systems are evaluated based on a flexibility factor, the “fraction below the annual peak to which conventional generators can cycle”, such that a system with factor 100% would be flexible to cycle conventional generators to zero load (no minimum stable generation limit) and accommodate large shares of variable energy sources [20]. While understanding the limits of successful operational conditions is very useful for both operations and planning, these do not provide information about the likelihood that a system can remain within these conditions or how to practically expand them.

The Insufficient Ramping Resource Expectation [41] aims to inform long term generation planning by quantifying the “expected number of observations when a power system cannot cope with the changes in the net load, predicted or unpredicted”. This metric can be great for comparing different system configurations and portfolios based on which will provide more reliable electricity services, but does not yield any insight into the nature of the shortfalls or what could be done to alleviate them.

Other flexibility metrics focus on resources within electricity systems. For example, the Max Power Temporal Ratio [43] indicates whether a resource is better suited as an energy resource or as a power capacity resource by computing the “maximum duration a [resource] can sustain its maximum power variation with respect to its nominal power”. This metric, measured in time, can be used to classify flexible resources, but must be combined with other information about physical resource constraints to know whether a resource is appropriate for a particular system need.

One demand flexibility index [59] includes components about variation and dispersion of activities throughout the day (difficult to shift many activities in short time), synchronization with other people (how difficult to shift social practices), shared activities (more difficult to shift when others involved), and spatial mobility. Similarly, the Flexibility Index of Aggregate Demand and the Percentage Flexibility Level [53] are probabilistic measures of electricity customer flexibility, based on likely load variation and user behavior, and therefore an indication of demand side management potential. These demand-side indices have found ways to quantify some of the social factors which influence demand response potential, though they rely on limited and highly context specific data about activity patterns and incentives to change behavior. More importantly, they focused on the ability to provide system flexibility, rather than the need for system flexibility.

Though a single index output score is appealing for simplicity and comparability, it cannot capture the various dimensions and tradeoffs which are inevitably involved in arriving at a single metric. At the other extreme, a flexibility tracker of 80 distinct key performance indicators of physical, economic, structural, and social factors attempts to capture system readiness for scaling up variable renewable energy [66]. This tracker is quite comprehensive and captures the interdisciplinary nature of electricity systems, but its many dimensions are unwieldy and it does not satisfy the minimal data required criterion. In each case, significant expertise is required to meaningfully interpret and act on the output metrics.

2.1.3 Sources of Flexibility

A variety of resources in the electricity system contribute to system flexibility, including flexible power generation, demand side resources, energy storage, and network configurations.

Supply

Flexibility needs have traditionally been met by the supply side, matching electricity generation to demand. Flexibility comes both from individual generators' ability to respond to changes and from having a diverse enough portfolio of dispatchable resources to use for different needs [67].

More flexible power generators have larger ramp rates, lower minimum stable generation levels, and shorter minimum durations on or off, enabling them to better follow net load and contribute to system balancing [67, 6]. Gas power stations in particular can ramp up and down relatively quickly and currently provide critical peaking capacity [19].

Fossil fuels are the current predominant provider of long-term system flexibility, as they can be stored at scale, with sufficient energy density, affordably, in stable conditions for years after extraction and processing.

Total installed capacity must be higher than the annual peak demand to allow a large enough margin for uncertainty in the availability of variable generation. Additional capacity can increase flexibility, in particular if the additional generation capacity comes from a diverse portfolio of options.

Demand

Demand side management (DSM) is becoming an increasingly promising resource for balancing system load. Rather than supply following demand, consumers could shift their electricity use to when lower-cost or less-polluting energy resources are available [68, 59, 53, 69, 70, 55].

Demand side management initiatives can be classified into "appliance-led" and "behavior-led" flexibility categories [55]. Appliance-led means shifts in demand are automated in response to an external signal without requiring user intervention. These appliances often have some type of storage which decouples energy demand from service provision, for example thermal storage in a refrigerator or heat pump which cycles on and off, while still maintaining the core service of temperature control within pre-set bounds. Behavior-led means humans could change their electricity use in response to an external signal, by using it at a different time or achieving a similar result with a different method (e.g. air drying laundry rather than using a tumble dryer).

In the UK, the potential for demand side management is very uncertain. Initial programs with industrial and commercial electricity users have been implemented and are slowly growing, though more research is needed into the realistic potential at scale [6, 17, 15]. For residential end-uses, demand response faces more non-technical challenges which may be barriers to scaling up but there is still large potential [71, 64, 19, 72].

Storage

Energy storage systems can contribute to system flexibility by providing either short term services, like frequency regulation, or long term services, like energy arbitrage to provide lower-cost or lower-carbon electricity [73, 6, 10]. To match demand and supply, energy may be stored for different durations, on the order of minutes, hours, days, or even seasons [25, 67, 73]. Pumped hydropower accounts for over 95% of the worlds energy storage capacity [73] though chemical batteries are increasingly becoming both technologically and economically feasible grid-scale resources and significant research is exploring options for hydrogen or other power-to-gas long term storage [2].

Section 2.2 includes more detail about estimating requirements for storage and sizing storage assets.

Networks

Networks facilitate access to power generated elsewhere, connecting locations with excess demand and with excess generation and expanding the options for dealing with changes in system load [40, 52]. Networks only increase flexibility if services are available elsewhere, so connections between systems with very similar demand and supply constraints or correlated needs would not increase flexibility.

For Great Britain, interconnectors with other grids in Europe will continue to be an integral flexibility resource [6, 19, 55]. Additionally, a more robust domestic transmission network will enable more wind power from the north to meet demand in the south, instead of curtailing the wind generation due to grid constraints [74].

As discussed in Chapter 1, this thesis focuses on the temporal dimension of flexibility requirements rather than on the ability of spatial networks to provide system flexibility.

2.1.4 Approaches to modelling flexibility

Modelling approaches can be categorized by their context, scope, and perspective. We focus on technical system-wide models of power system flexibility, as they are most relevant for the research undertaken in this thesis. Under technical models, we also consider those which incorporate economic, social, or political constraints and objectives into a primarily technical engineering framework. Non-technical models of flexibility in electricity systems, including models of markets, policy scenarios, or social behavior are not the focus of this research.

Bottom up

Most system flexibility models use a bottom up approach, increasing system flexibility by adding flexible resource components.

Optimization models are very commonly used. These could be for scheduling resources [75, 60, 52, 76, 62, 77, 57, 70], designing generation portfolios [38, 78, 79, 80] and flexible resource portfolios [5, 81, 69], and integrating operational and investment decisions [82, 72, 83, 45, 84]. However, because these approaches typically aim to minimize costs or perhaps carbon emissions, the results depend heavily on the assumptions about costs and technology parameters.

In a different bottom-up approach [47], physical constraints are used to compute upper and lower potential power outputs for each time step, which creates a a “flexibility envelope” or cone that changes over time.

All of these bottom-up approaches require knowledge of the resources the system has available and their specific technical parameters, and sometimes also their costs. With the continuing improvements in technical performance and rapid decreases in costs of renewable generation and storage technologies, it will be important to understand how robust the conclusions are to those assumptions.

Top down

Top down approaches look at the system as a whole, rather than as the sum of its components, and have been used to model flexibility requirements of electricity systems under different energy mixes [20, 58, 48, 49]. In some studies, flexibility requirements are presented alongside resource availability, including a high level resource dispatch model [20] and an abstract bottom up method to estimate resource flexibility [47].

There is considerable variability among energy mixes studied. Many studies focus only on very high penetrations of renewable energy, up to 100% variable renewables, to explore the limiting extreme cases [21, 20]. The impact on ramping requirements of the ratio between solar and wind, at various penetrations of renewable energy is studied in [48]. Even among studies which focus on 100% renewable energy mixes, there is considerable variation in assumptions about energy mixes, demand profiles, and available flexible resources [21]. Several other studies consider only wind power, at various penetration levels, and ignore solar power [83, 75, 45, 58, 79, 76].

2.2 Storage sizing

Storage requirements have been estimated for different penetrations of variable renewable energy in a variety of locations and scenarios [85, 20, 86, 87, 22, 88, 89, 90].

These sections discuss literature related to sizing storage, in particular regarding tradeoffs with generation capacity and the need for long duration storage.

2.2.1 Tradeoffs between storage and renewable overcapacity

Although several studies have shown tradeoffs between excess generation and total storage capacity [85, 91, 26, 92, 81, 23, 90], there is no consensus about whether overcapacity is desirable or for which types of systems and contexts it may be worthwhile. It is worth noting that existing non-renewable generation capacity exceeds demand, providing reserve and flexibility. The difference is the curtailment of potentially useful renewable power.

Curtailing renewable energy generation is generally seen as wasteful, expensive, or something to be avoided unless necessary, for example to deal with transmission constraints, system balancing, or network security issues [93]. Some approaches explicitly aim to avoid curtailing renewable generation [94, 24] or evaluate systems with higher curtailment as worse [92]. Others quantify costs and carbon emissions that could have been avoided if the renewable energy had been used instead of curtailed [95].

However, not all studies begin with the premise that curtailment should be avoided. Curtailment may be valuable and could help integrate variable renewable energy sources under certain conditions [96]. Although Steinke et al. [91] and Budischak et al. [26] agree that oversizing renewables could reduce the need for storage, they disagreed in 2013 about whether this is worth considering. Budischak et al. conclude that a cost-minimizing electricity system for part of the USA could generate as much as three times the energy demanded to reduce the need for expensive storage [26], while Steinke et al. find that an excess installation of renewables does not reduce system costs and is therefore not worthwhile [91].

These diverging conclusions depend heavily on assumptions about resource availability and costs. Given how quickly costs of both generation and storage technologies have been falling in the past decade [33, 36] and uncertainty about future cost trajectories, there is a need for understanding the robustness of conclusions to cost assumptions.

Since then, others have shown that some excess generation and corresponding curtailment may be optimal and enable higher penetrations of renewable energy. Perez et al. distinguish between reactive curtailment (which currently happens in response to network challenges) and proactive curtailment [97]. They show that oversizing of solar photovoltaic (PV) installations combined with intentional proactive curtailment is more cost effective in Minnesota, USA over a ten year simulation. Shaner et al. [23] show that overcapacity reduces total storage capacity requirements significantly across a range of wind to solar ratios and estimates that overcapacity would be less expensive than relying on storage, especially for interseasonal balancing in the USA, using a 36 year simulation.

A single-year case study of Great Britain [89] concludes that small amounts of overcapacity are cost-optimal, with 5% overcapacity of renewables reducing the storage energy capacity required by nearly 50%. Some of the analysis presented here extends this work on Great Britain, studying the effects of greater overcapacity and using multiple years to fully understand tradeoffs involved in terms of storage requirements and system costs.

While tradeoffs between renewable generation capacity and overall storage requirements have been well-established in the literature [85, 91, 26, 92, 81, 23, 32], it has not yet been established where the reductions in storage capacity could come from or which types of storage would be displaced. Overall storage would comprise a portfolio with different types of assets suited for different applications and energy shifting timescales based on their properties (e.g. energy to power ratio, efficiency, self-discharge, reliability). To understand which types of assets are required in the storage portfolio and which ones might be displaced by overcapacity, it is useful to understand the roles that the different assets would play and the amounts of time energy would need to be stored for under different scenarios.

2.2.2 Long term storage and flexibility needs

Few studies estimate the timescales required for energy shifting or amounts of time for which energy would need to be stored. Most approaches assess adequacy of portfolios with different types of storage resources, analyzing how much demand is met or how much variable renewable energy is curtailed [22, 23, 24], rather than the system requirements, although one approach uses monthly data to make a case for interseasonal shifting [25].

Existing analyses which integrate multiple storage types and timescales [26, 27, 28, 98] or which explicitly address long-term or interseasonal storage [27, 29, 24, 30, 28, 99, 31, 100] produce capacity estimates which rely on assumptions about technology parameters and costs. Therefore, while these papers show that long-term storage could have a role to play in those defined scenarios, they do not address whether or under which conditions a power system might require long-term energy shifting.

This thesis differentiates between the amounts of time for which energy must be shifted or stored and capacities reported in units of time. It is important to note that storage capacity can be reported as a duration, for example the time to discharge fully at maximum power [24, 101] or time for which it can meet average demand [91, 23]. While this metric characterizes a storage device's ability to provide flexibility, and is relevant for constructing appropriate portfolios of flexible technologies, it does not provide insight into the length of time for which energy would actually be stored or system flexibility requirements.

Given the uncertainty about future energy system configurations, it is important to investigate how these storage requirements depend on the generation mix [32], rather than assess the optimal strategy for a particular set of conditions. Additionally, the costs of renewable generation technologies, storage technologies, and other flexible resources have been rapidly falling [33, 34, 35, 36]. Therefore, the cost-minimizing combination of generation and storage could change based on how these technologies' costs develop and fall relative to each other over time and there is a need to better understand investment strategies for a wide range of potential cost trajectories.

Additionally, there is a need to understand how these requirements will change in future power systems. While many of these studies investigate the need for storage in systems with much higher penetrations of solar and wind, there is a need to also understand how changes in demand would affect storage sizing requirements. In particular, large trends such as electrification of vehicles and heating could affect the need for storage and flexibility in these systems.

Time horizon

The studies in literature use different time horizons for analysis, investigating system requirements using simulation time horizons of one day [58], two weeks [49], one year [48, 20, 89], and multiple years [23, 90, 102]. Most of the optimizations use short time horizons, preventing adequate investigation of interseasonal storage [103].

To properly investigate the need for long-term or interseasonal flexibility, multi-year time horizons would be required to account for the variability in both weather patterns and demand patterns. The number of years of included in the simulation time horizon is usually determined by data availability rather than by an optimal or minimum number of years for system analysis. Simulations of one year would be an absolute minimum requirement and these would not account for interannual variability.

2.3 Gaps that this thesis aims to address

This thesis aims to address four gaps that have been identified in the literature.

First, it aims to estimate requirements for flexibility, while being agnostic to the technologies which might provide that flexibility. Most flexibility modelling focuses on the availability of flexibility rather than the flexibility required by the system. Furthermore, most investment and planning models rely on available technologies, including assumptions about specific technical parameters and cost. Given the potential for need for long duration or interseasonal flexibility, for which we do not have available technologies which have been deployed at scale, understanding the underlying need for flexibility can help inform which flexibility resources to invest in – not just for installation, but also for research and development. The methods to address this gap are discussed in Chapter 3 and then illustrated using the case of Great Britain in subsequent chapters.

Second, it aims to develop methods to understand the different timescales required for flexibility. For appropriate system planning, there is a need to understand how much flexibility will be needed over these different timescales, because the technologies used to store energy for an hour may be different from those used to store energy between seasons. Most existing assessments which incorporate flexibility assets which operate over different timescales rely on highly technology specific assumptions and often cost assumptions. These studies show whether a particular portfolio of assets could meet demand in that set of conditions, rather than describing the underlying needs to shift the energy over those timescales.

The methods to address this gap are discussed in Chapter 3 and then illustrated using the case of Great Britain in subsequent chapters.

Third, while some have begun to investigate sensitivity of flexibility requirements to generation mixes, much more work remains on the sensitivity of viable resource portfolios to energy mixes. There is not consensus in the literature about the value of excess renewable generation or the optimal solar wind ratio in the generation mix. Furthermore, many studies in literature do not use sufficiently long time horizons to capture potential interseasonal flexibility requirements, rendering their results of overall storage requirements underestimates. In particular, much of the multi-annual analyses have been done on the United States and on Europe, but these results will be location specific. There is a need to show how the generation mix would affect flexibility requirements in Great Britain, in particular the need for flexibility over different timescales. This gap is addressed in Chapter 5.

Fourth, given the likely changes in electricity use going forward, it will be important to investigate how flexibility requirements and resource portfolios depend on assumptions about demand profiles, particularly electrification of transportation and heating. Many system models ignore demand side flexibility options or use broad assumptions to approximate their potential. Most of the storage sizing and investment planning models do not include these demands Although a large and growing body of research looks at the impact of EVs or electric heating on the power system and its requirements, there is still a gap surrounding the impacts of these massive demand shifts on the need for flexibility and storage specifically. Furthermore, there is a need to understand how making these demands flexible would affect the remaining system need for flexibility. This gap is addressed in Chapter 6.

3

How to characterize temporal flexibility requirements of electricity systems

This chapter aims to address the question of how to characterize flexibility requirements over multiple timescales in highly renewable power systems. Specifically, it addresses each of the following sub-questions.

1. How can overall temporal flexibility requirements be characterized?
2. How can flexibility requirements at different timescales be identified?
3. How can the utility of different levels of demand flexibility be tested?

For system planning, it is helpful to understand not just how much energy would need to be shifted overall, but how much of that would need to be shifted by a few hours, how much by a few days, and how much by several weeks, or by months to deal with interseasonal effects. Quantifying both the requirements themselves and how they are differently affected by generation mix or demand patterns can help inform investment and planning decisions.

3.1 Research Questions

The first research question is how to characterize the overall temporal flexibility requirements. Systems with large amounts of inflexible generation require the flexibility to shift electricity demand and supply through time and space to balance the system and keep it stable. Electricity system flexibility has several different dimensions, including energy, power, ramping, and timing, which are discussed further in Chapter 2. The requirement for flexibility studied here is conceptualized as the requirement to shift energy or power across space and time; here, the focus is on the temporal dimension, shifting energy through time.

The second research question is how much energy shifting is needed over different timescales. Understanding needs over multiple timescales is important because electricity systems will need some flexibility resources to balance the system on the order of seconds or less, while other resources will be required to operate over hours, days, weeks, or even seasons. This work aims to understand the temporal requirements themselves, not whether a particular set of flexible resources or specific technologies could meet demand in a specific context with a certain level of reliability. When discussing flexibility requirements, the issue is not which technology will win out, but rather which range of technologies will be required. Understanding the different timescales of energy shifting required helps address this question.

The third research question is how to test the utility of different potentially flexible resources in meeting electricity demand, specifically what effect different degrees of flexibility in electric vehicle (EV) charging and electric heating might have on the remaining flexibility requirements. If one could use a flexible resource, like a fleet of electric vehicles or heat pumps, in a particular way and displace the demand by up to a certain amount of time, one could ask how much the remaining flexibility requirements would be affected. For example, if allowing electric heat demand to be shifted by up to six hours rather than by one hour makes a significant difference to the need to install other flexibility capacity, this could make the case for insulating buildings even stronger. This research can help address whether certain technology development or social practices have additional benefits and might strengthen the case for pursuing particular policies or research.

3.1.1 Definitions and assumptions

To answer these questions and draw meaningful insights, it is important to clarify the scope, definitions, and assumptions of this work.

As described in Chapter 1, the flexibility requirements here refer to temporal flexibility requirements. This could be achieved through storing energy, effectively shifting the timing of generation with an efficiency factor, or through shifting the timing of demand. In the case of storing energy, the capacity requirements are the minimum power and energy capacity of the aggregated storage assets. In the case of shifting energy use away from when it would ideally be demanded to better align with generation, the required capacity results are effectively the accumulated energy which has been displaced in time. This can be thought of as a measure of accumulated discomfort. Throughout this document, the word *storage* is used to represent both concepts, so storage profiles and storage capacity requirements reported represent the profiles and required capacities of all flexible resources with a temporal dimension, not only physical energy storage devices.

These methods assume that energy is stored or displaced for the shortest amount of time possible. This yields the minimum storage capacity which could meet demand under each system configuration, or the minimum amount of accumulated discomfort from displacing demand to times when it could be met. By storing energy for the shortest possible amount of time, energy is stored as late as possible and no excess energy is stored, ensuring the output identifies the minimum energy capacity required. This strategy provides good estimates for the minimum energy capacity and power capacity required for discharge, though the charging capacity using this method would likely be an overestimate.

Even from an energy flexibility perspective, energy does not necessarily need to be shifted through time. Demand could be unmet or avoided or there could be additional energy use which wasn't originally demanded. This analysis focuses primarily scenarios where all demand is met, without investigating reliability, and therefore focuses only on shifting energy through time.

Focusing on shifting energy is appropriate here due to the national scale of the problem and the time resolution of data available. At an individual building or resource level, it would likely be necessary to maintain a certain power profile shape when shifting that energy through time. However, at a regional or national scale, it is reasonable to assume that these individual power profiles could be viably aggregated using appropriate control strategies, such that the energy could be shifted through time into an overall power profile required to ensure system power balance at every time step.

We use a resource portfolio to refer to the concept of using a range of technologies which are appropriate over different timescales, but this is still agnostic to the specific technologies used. Rather, there are different classes of assets, which can be defined by the lengths of time over which they offer flexibility. The flexible resource portfolios here refer to portfolios of these classes, but each class of assets could have multiple specific technologies, and indeed a specific technology may be able to serve needs across two or more classes.

The model assumes perfect foresight of both demand and supply, with known demand and weather patterns. This is acceptable for models which are intended to inform planning, investment, and policy decisions, rather than real time operation. The results also rely on the assumption that future weather patterns and baseload demand patterns are relatively similar to recent historical patterns. While future weather and demand patterns will certainly differ from current ones, historical patterns provide reasonable and more importantly credible profiles to use for analysis and the potential effects of climate change and electrification of electric vehicles and heating are discussed in subsequent results chapters.

Overcapacity values given refer to energy overcapacity, relative to energy demanded over the entire time horizon of each simulation. An overcapacity of 10% (or 1.1x) means that 10% more energy is generated than is demanded over the entire simulation. The excess generation can be used to account for inefficient storage or can be curtailed, depending on system parameters. This is the same definition of overcapacity used in related literature ([23, 89] among others). It does not refer to the additional installed power capacity over peak power demand.

Inflexible generation and renewable generation are used to refer to the combination of solar and wind generation. Solar generation is assumed to only come from photovoltaics (PV) and wind generation includes both onshore and offshore wind. These are referred to as inflexible even though curtailment may provide some flexibility from solar and wind generation. Forms of dispatchable generation, including renewables like hydropower and biomass, are not included in the scope.

In all simulations systems are 100% reliable and meet all electricity demand, unless otherwise specified. Not meeting demand in these scenarios could imply several potential scenarios – from actually not meeting the demand, to having that demand met by other flexible generation such as dispatchable generation or from interconnectors.

In the subsequent simulations, storage and other flexibility resources are assumed to be 100% efficient, unless otherwise specified. This is useful because assuming perfectly efficient storage means the results reflect the minimum system requirements and are agnostic to the technologies used to provide the energy shifting service. However, because efficiency is so vital to understanding minimum storage capacities required, the effects of efficiency are studied and reported separately.

Spatial flexibility in the form of interconnectors is beyond the scope of this work and not included, unless otherwise specified in future simulations. Network and transmission constraints are ignored. This is appropriate to study minimum temporal flexibility requirements, as removing the spatial constraints means all spatial flexibility within the system is already being utilized.

3.1.2 Parameters of simple case study

To illustrate the methodologies used, a simplified example scenario and data for one week in Great Britain is used. The parameters and specifications for the example week are summarized in Table 3.1.

In subsequent chapters, they are applied to the case of Great Britain, but the methods can be applied to other locations with different demand and weather patterns. Further information about the data sources used for analysis in the rest of the thesis is covered in Chapter 4.

Demand for electricity follows the pattern shown in Figure 3.1. Electricity supply is provided only by solar PV and wind generation, with no nuclear or dispatchable generation. The solar and wind capacity factor profiles are shown in Figure 3.2. These are real-time capacity factors at hourly resolution, not annual capacity factors. It is acceptable that these do not reach 1 at any point in this week, as this week may not have the windiest or sunniest day.

The solar PV and wind power installed are sized such that the generation mix is 25% solar and 75% wind in terms of energy supplied, based on the optimal storage size minimizing mix from a one-year study of GB [89], and with some buffer so the installed generation could potentially generate 10% more energy than demanded over the course of the simulation.

Table 3.1: Example case specifications

Parameter	**Value**
Location	Great Britain
Dates	April 23-29, 2016
Demand (TWh)	5.55
Overcapacity	10%
Solar/wind mix	25%/75%
Solar installed (GW)	55.27
Wind installed (GW)	79.73
Efficiency of energy shifting	100%

The following sections present approaches to addressing the key research questions. Section 3.2 describes the approach to characterizing overall system flexibility requirements as the need for shifting energy through time. Section 3.3 describes three approaches for disaggregating the overall flexibility requirements into requirements over different timescales. Section 3.4 explains the method used for creating flexible demand profiles, for example for EV charging or electric heating, based on an initial

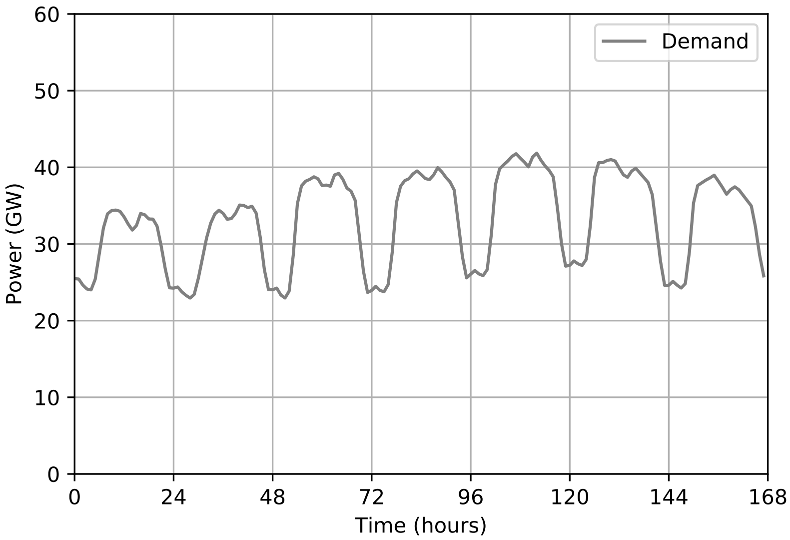


Figure 3.1: Demand data for example case used to illustrate methods.

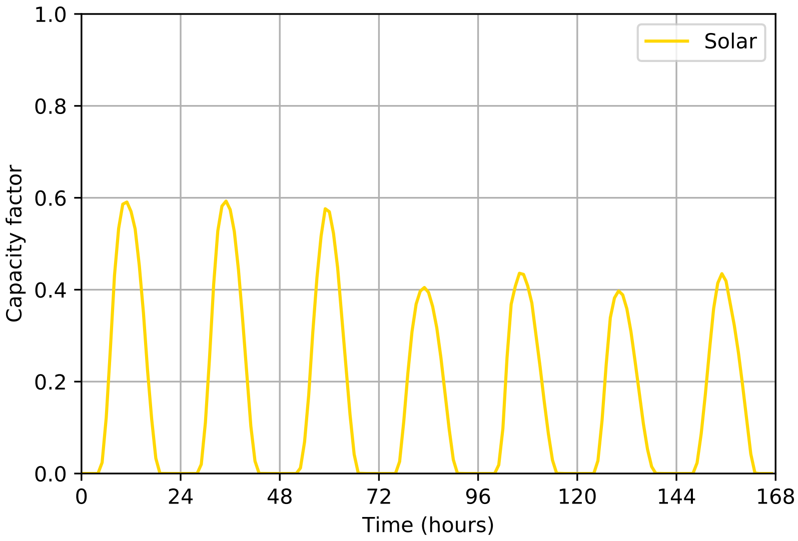
inflexible demand profile and a constraint about the degree of flexibility in that demand. Sections 4.1, 4.1.4, and 4.1.5 then describe the data and model inputs which are used for the Great Britain case study.

3.2 Characterizing flexibility requirements

Characterizing the flexibility requirements of future power systems is useful because it could yield insights for planning and investment decisions under different potential future conditions. Therefore, the requirements are measured in terms of the minimum capacity of total flexible resources which could meet the requirements. This minimum required capacity of aggregated flexible resources is measured in terms of energy capacity and power capacity required, which are common technical metrics of installed asset capacity in power system.

3.2.1 Net load

System flexibility is required to address potential imbalances and between supply and demand. The misalignment between demand and inflexible renewable generation is shown in Figure 3.3 for the example case. This misalignment is often



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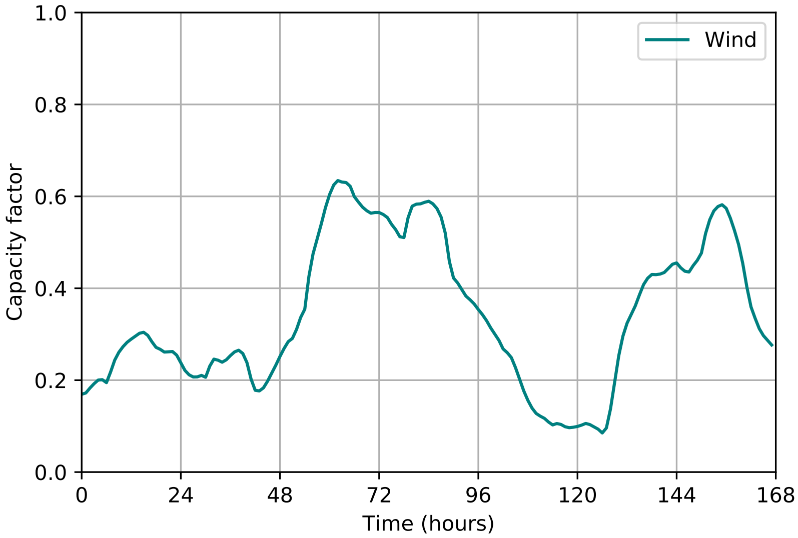


(b)

Figure 3.2: Renewable generation real time capacity factor data for example week.

characterized by the net load, which is found by subtracting inflexible renewable generation from demand.

The amount of energy shifting needed depends on the misalignment between demand and supply, which is characterized by the net load profile. The net load is found by subtracting inflexible renewable generation from demand, as in Figure 3.3. To calculate generation profiles, the wind and solar capacity factor time series are scaled such that energy generated over the simulation is enough to meet energy demanded plus any energy overcapacity.

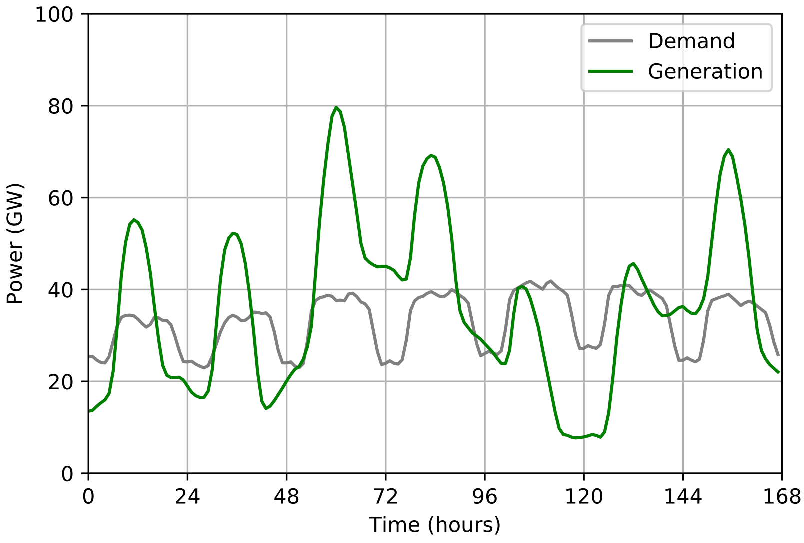
The rate of change in the net load profile is shown in figure 3.4. Ramp rate is an important consideration for flexibility, as it representations how the system is changing or needs to change, how quickly and in which direction. However, ramp rate is not reported going forward as it is not an appropriate metric to use in this context for several reasons. Most importantly, the temporal resolution of this data is hourly, but most flexible resources are able to ramp up and down on shorter timescales. Additionally, the analysis is looking at aggregate resource capacity, not of an individual asset or even individual resource class, so the output of aggregate is less meaningful as different combinations of assets could be operated to achieve a wide variety of different ramp rates.

In this example case, the net load shown in Figure 3.3 is electricity demand minus the inflexible renewable generation. Values below zero indicate excess supply, while values above zero indicate supply shortfall and unmet demand at those times.

3.2.2 Energy shifting requirements

One way to quantify the energy shifting required is to imagine that energy shifting is accomplished by a single flexible asset, although in reality this would be an aggregated portfolio of many smaller assets. Sizing this single large asset can yield insight into the amount of energy shifting required and the corresponding sizing of aggregate flexible resource portfolios.

This asset could be thought of as a storage asset, which would physically correspond to shifting supply later in time, though resulting capacities could equally used to size resources for shifting demand earlier in time. One could ask, at any given point in time what is the minimum amount of energy which would need to be in storage to meet the remaining demand. Shifting energy in the opposite direction (i.e. moving demand later or supply earlier) is less physically intuitive as a “storage” asset but works theoretically in the same way. The physical meaning of the resulting resource size would be the cumulative displaced or unmet energy



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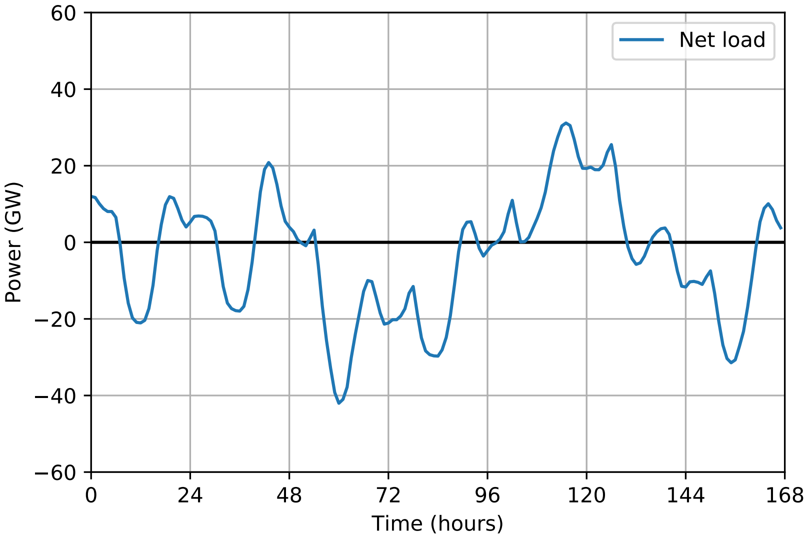


(b)

Figure 3.3: Demand and total renewable generation profiles and for example week (above) and net load profile for example week found by subtracting inflexible variable solar and wind generation from demand (below).

demand at any time, while the power capacity would be the maximum power demand displaced at any time.

A time step simulation is developed and uses the net load profile to estimate the power and energy requirements of storage. The amount of energy stored at each

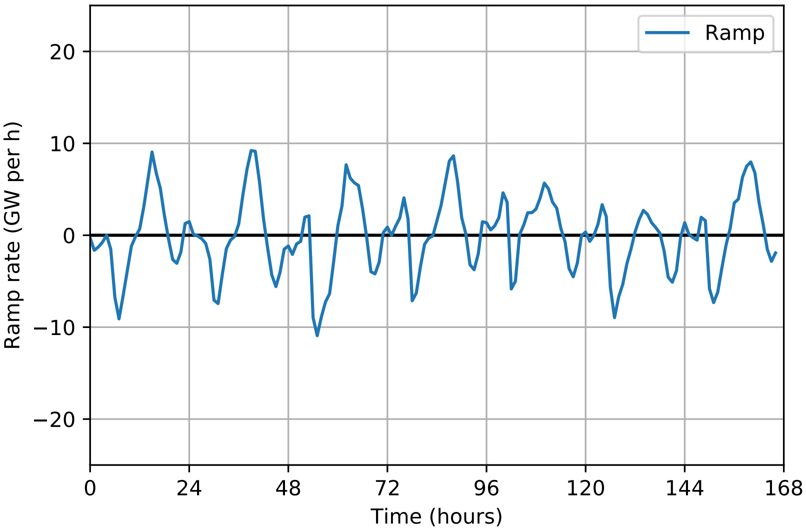


Figure 3.4: Rate of change of net load profile.

time step is found by calculating the required amount of stored energy to meet the remaining unmet demand. This ensures there is sufficient storage, but not more than required for system to be balanced at all times. All demand is met by variable renewable generation or storage. Storage is sized according to the flexibility needs, so any instantaneous shortfall in energy will be provided for by storage that was designed to release previously stored energy during these times.

The algorithm begins at the time step where the integral of the net load is most positive, as this is when there is most accumulated demand for storage to meet, and therefore when the total storage would have completely discharged if all demand is met. The algorithm progresses backwards in time through the net load profile to create a storage profile, shown in Figure 3.5 for the example week. When it reaches the beginning of the net load profile, the algorithm loops around to the other end of the net load profile and proceeds backwards until the time step where the algorithm started. This ensures that storage begins and ends with the same state of charge and avoids the need for multiple loops through the net load profile.

The value of the storage energy profile at each time step is the amount of energy which must be in storage to meet remaining net demand, accounting for charging and discharging efficiencies. The minimum storage size required is the maximum amount of energy in storage at any time.

This method can account for differences of charging and discharging efficiency. Running simulations with perfectly efficient energy shifting yields the minimum possible size required and is therefore a useful limit to understand. Less than perfect efficiency would require additional capacity to ensure all demand is met. Furthermore, assuming perfectly efficient storage means the results are purely reflective of the minimum system requirements and are agnostic to the technologies used to provide the energy shifting service.

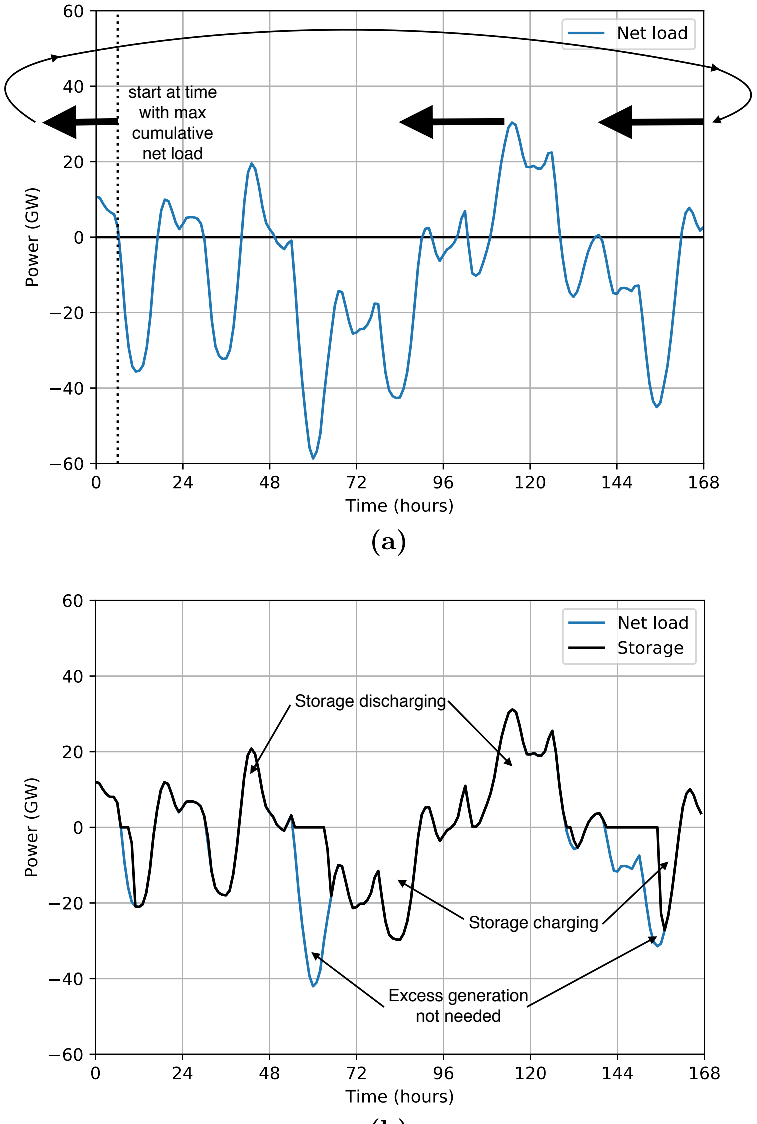
Figure 3.6 shows a potential charging and discharging profile for aggregated storage resources which could meet the flexibility needs. The discharging profile is entirely determined by the demand to be met. Therefore the maximum value is the minimum discharge power required for total storage, which is 31.2 GW for the example week. The charging profile here ensures energy is stored for the shortest possible amount of time, but other charging profiles would be possible. The excess supply which is not stored, indicated in Figure 3.6 by the part of the net load profile which does not overlap with the storage profile, would be curtailed.

Figure 3.6 also shows the minimum amount of energy which would need to be in storage at any given time to meet remaining demand. This is not necessarily the storage profile which would be used, but it is useful for for determining capacity requirements, as the peak represents the minimum storage size needed. For the example week, this is 480.2 GWh.

The periods of time where stored energy is zero correspond to the times when excess supply is curtailed. If a different charging profile were used, these periods would be flat and unchanging (or decreasing slightly due to self-discharge, which is assumed negligible in this illustrative example week), but not necessarily at zero.

Validation

This method for sizing overall storage was validated against Shaner et al.'s storage model [23]. While this model is valuable for comparison and validation, this



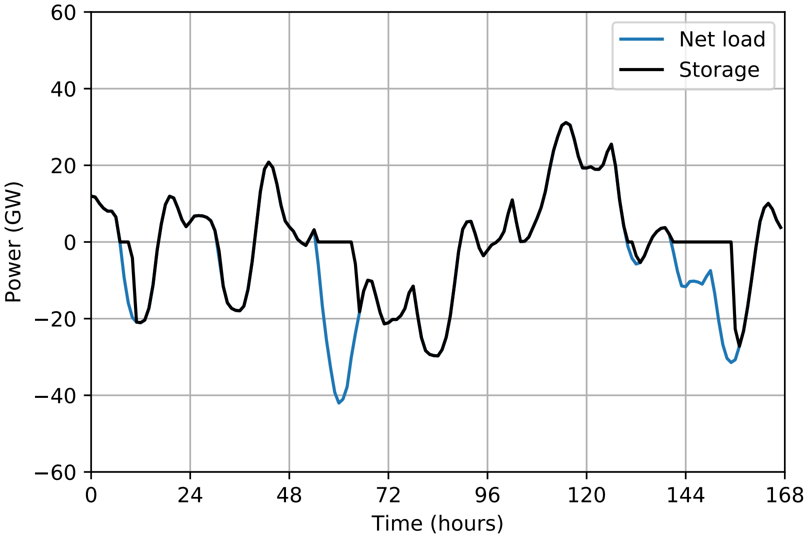
(a)

(b)

Figure 3.5: The simulation begins at the time step where the cumulative net load is most positive and progresses backwards through time to calculate the amount of energy which must be in storage at that time step to meet remaining unmet demand. Power not needed is curtailed.

work does not simply reproduce their model. Their model is primarily used for reliability and storage size in an input, while size is an output of the methods described here and these methods are developed further in subsequent sections to add disaggregation over timescales. Although they serve different purposes, their model can still be used for validation, as their 100% reliable scenario corresponds to meeting all demand as in the analysis in this thesis.

To validate results results from the model, the overall storage model was



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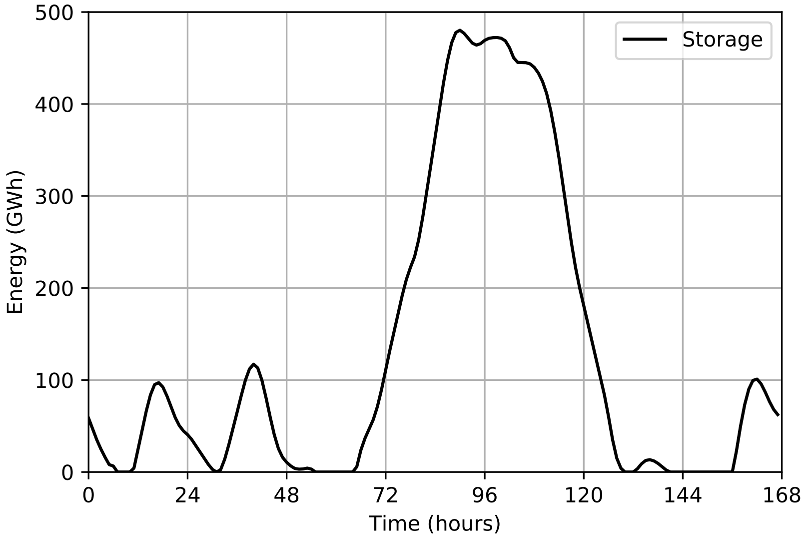

(b)

Figure 3.6: Example storage profile if all flexibility needs were met by storage and energy were stored for the shortest possible amount of time. The maximum value of the power profile (above) represents the minimum discharge power required for all aggregated flexible resources. The the energy profile (below) represents the minimum amount of energy stored at any given time and its peak represents the minimum aggregate storage size required.

compared with Shaner et al.'s reliability model [23] in two ways. First, Shaner et al.'s model is applied to the same GB data used in this analysis to test outputs. In addition to the results for the example week shown here, results for multiyear simulations can be found in the Appendix. Second, our model was applied to data from the continental United States (USA) to attempt to replicate their published results.

Shaner et al.'s model can be implemented exactly as published, although it requires the storage size to be an input. To enable comparisons, a simple bisection algorithm is used to test different input storage sizes, with stopping criteria of guesses within one kilowatt-hour or after 20 iterations. For the example week presented here, Shaner et al.'s model [23] yields 480.7 GWh. This aligns extremely well with the minimum storage size estimate for the example week in Section 3.2.2.

The model used here and described in Section 3.2.2 was applied to the USA using the same publicly available data [104, 105] to replicate Shaner et al.'s results.

Table 3.2: Comparison of tradeoffs between overcapacity and storage size, using Shaner et al.'s reliability model [23] and the model presented here for the continental USA. Storage size is measured in time for which storage can meet mean demand.

Storage size	**Solar / wind ratio**	**Overcapacity [23]**	**Overcapacity This model**
32 days	25% / 75%	1.14x	1.14x
	75% / 25%	1.13x	1.13x
4 days	25% / 75%	1.70x	1.70x
	75% / 25%	1.68x	1.68x
12 hours	25% / 75%	2.28x	2.28x
	75% / 25%	3.07x	3.07x

Table 3.2 shows that this model yields the same results as published values [23] for combinations of overcapacity and storage in a 100% reliable system when applied to the continental United States. The agreement is not surprising because the energy capacity required calculated using this overall storage requirements model is theoretically equivalent to the minimum size for 100% reliability in their model.

In Table 3.2, storage size is measured in units of days and hours, as originally published. These capacities reported in units of time measure the amount of time for which it can meet average demand and should not be confused with the amounts of time for which energy must actually be stored in that device, which is discussed in subsequent sections. While this metric characterizes a storage device's ability to provide flexibility, it does not provide insight into the lengths of time by which energy would need to be shifted.

3.3 Energy shifting requirements over different timescales

This section shows how the novel application of three methods can address the second subquestion of characterizing flexibility requirements over multiple timescales.

Overall system flexibility requirements will be met by a portfolio of multiple storage resources with different parameters. These resources are differentiated here by the timescales of energy shifting they are able to meet, or the amount of time they can store energy for.

To identify flexibility requirements at different timescales, the single flexible asset can be disaggregated into a portfolio of other assets which operate over different timescales.

This work aims to understand the temporal requirements themselves, not whether a particular set of flexible resources could meet demand in a specific context with a certain level of reliability. Therefore, it is important that the disaggregation strategies are agnostic to the types of resources which could be used to meet the needs and do not depend on technology parameters, costs, or emissions.

One could later assign particular resources to each identified need and create a portfolio of resources which could meet demand. However, the resulting resource portfolios would be unlikely to be optimal from a cost or emissions perspective as that information was not considered when creating them.

Different disaggregation strategies produce different estimates for the amount of energy which would need to be shifted for short time horizons or long ones. This is expected, as multiple different resource portfolios could likely be operated in various ways to meet demand.

By using multiple independent disaggregation strategies and testing how the results depend on generation mix or demand profiles, one can assess which trends are common across strategies and which are specific. The common trends can yield insight into relationships between flexibility requirements at these timescales and system characteristics, while the strategy-specific results can yield insights into possible flexible resource portfolio operation.

The methods chosen should be distinct enough to produce independent results, should not rely on additional assumptions (e.g. about costs or efficiencies), should be well-established in other contexts, and should be straightforward to implement. They are intended to be illustrative, to enable test effects of other system parameters on flexibility requirements at different timescales, and do not necessarily yield optimal or realistic storage portfolios.

Based on these criteria, three different disaggregation methods are used. Two are well defined control algorithms, first-in-first-out (FIFO) and last-in-first-out (LIFO), where each unit of energy stored can be tracked as it enters and leaves the aggregate store via charging and discharging. The other method is a frequency analysis technique, using finite impulse response (FIR) filters to identify components of the overall storage profile which charge and discharge with different frequencies. The following subsections describe the implementation of these methods for storage timescale disaggregation in more detail.

3.3.1 First in first out (FIFO) method

First in first out (FIFO) algorithms are used to keep track of units of assets as they enter and leave a store or queue. In this case, those units are units of energy. This works well in the case shifting energy through time, whether that is provided by traditional energy storage or shifting demand.

The FIFO strategy is chosen for its straightforward nature and because it avoids keeping energy stored for the longest times. FIFO is most similar to the operation strategy for total storage used by some existing studies [106, 23], although they do not keep track of how long energy was actually stored. The simulation progresses through time-steps, charging and discharging the total store chronologically, keeping track of when each unit of energy was stored and when it was discharged.

The FIFO strategy is illustrated first on a stylized net load profile of ten time steps and then on the example week.

Figure 3.7 shows how FIFO could be applied to a stylized net load profile, where each unit of energy is labeled with a letter when it is charged (net load less than zero) and when it is discharged (net load greater than zero). This enables calculating how long each unit of energy remained in storage before being used and therefore estimating the need to shift energy for different amounts of time. For example, the units of energy labeled A and G are stored for only one time step, while the unit of energy labeled B is stored for four time steps.

One result of applying this FIFO algorithm is a distribution of timescales for which energy is stored and therefore for which energy would need to be shifted.If a particular portfolio of resources with certain characteristics were available, this distribution could be disaggregated at different cutoffs and used to identify which energy shifting needs could be met by each resource or what gaps would remain to be filled.

These units of energy can be sorted into groups based on how long they are stored for. In the stylized example, these are disaggregated into three groups based on the amount of time energy is shifted for: one time step (A, G), two to three time steps (C, D, E), and four or more time steps (B, F). These three different types of requirements could be met using different resources. After separating the different units of energy shifted into groups, new profiles can be created for each group. The corresponding power and energy profiles for each resource are shown in Figure 3.8.

FIFO is also applied to the example week to illustrate how it can be used to create profiles for flexible resources which operate over different timescales. Figure 3.9 shows the distribution of how much time energy is stored for in the example week, if the total storage were operated using a FIFO strategy.

To illustrate how this strategy can be used to disaggregate the overall profile into different types of flexibility requirements, a daily cutoff is used for the example week. In subsequent chapters, the analysis uses daily, weekly, and annual cutoffs, chosen based on patterns identified the demand profile. However, the method would

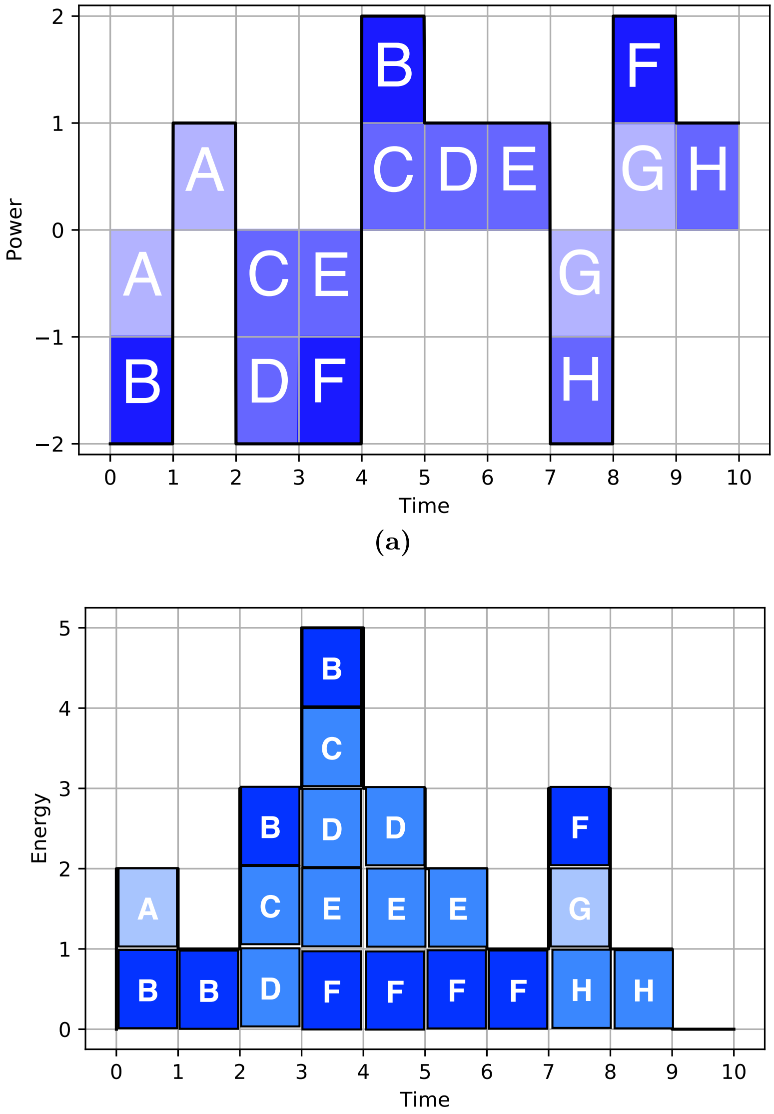

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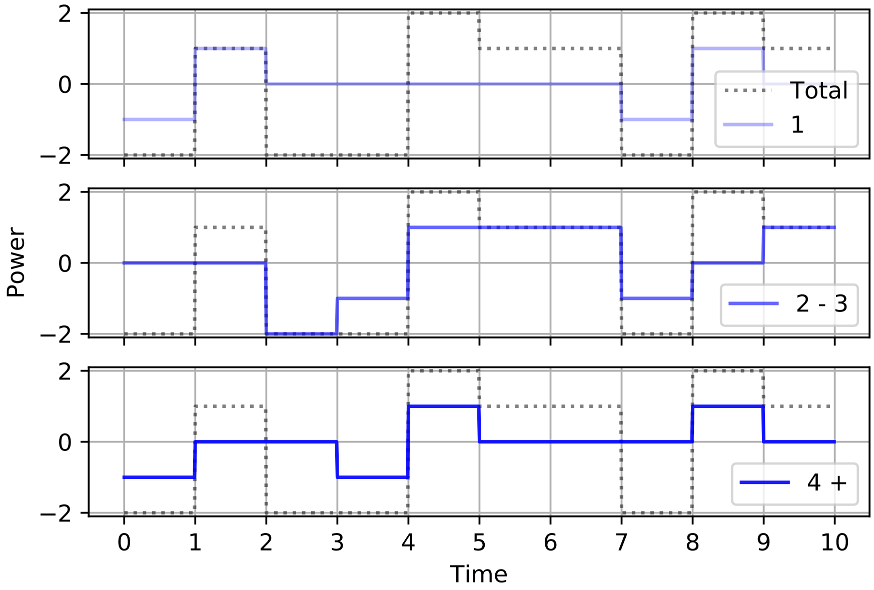
Figure 3.7: Illustration of first in first out (FIFO) method for stylized example net load profile. Each unit of energy is labeled with a letter when it is charged (power less than zero) and when it is discharged (power greater than zero).The darker colors signify units of energy which are stored for more time, while lighter colors are stored for less time.

work with any number of cutoffs at any point, so the most relevant timeframes for each context could be chosen.

For the example week, this yields storage profiles for energy stored for less than one day and energy stored for more than one day. The corresponding power and energy profiles are shown in Figure 3.10. In this example, it appears the two assets operate at different times with only one in use at each time step, but



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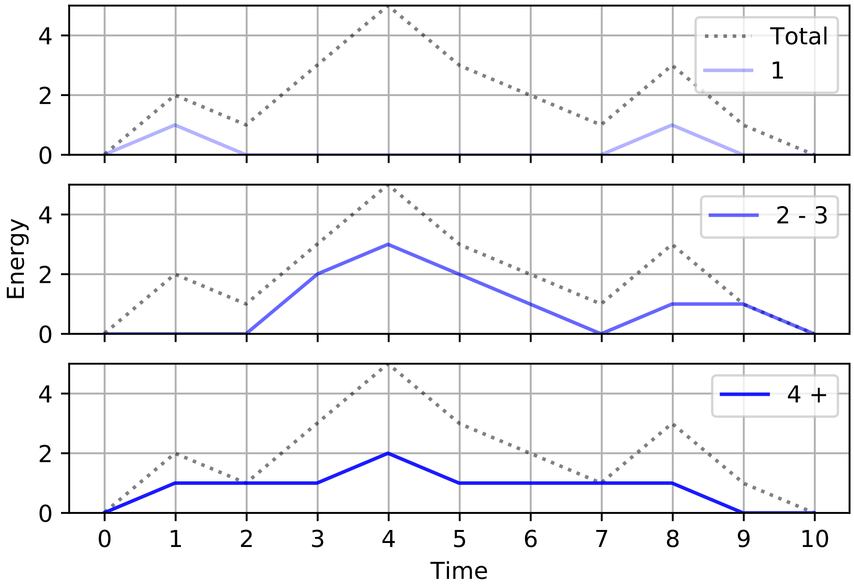

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Figure 3.8: Power and energy profiles for three flexibility resources which can shift energy for different amounts of time, created using FIFO to disaggregate overall energy shifting needs for the stylized example.

this is not necessarily the case when there are more assets from multiple cutoffs operating over much longer time horizons.

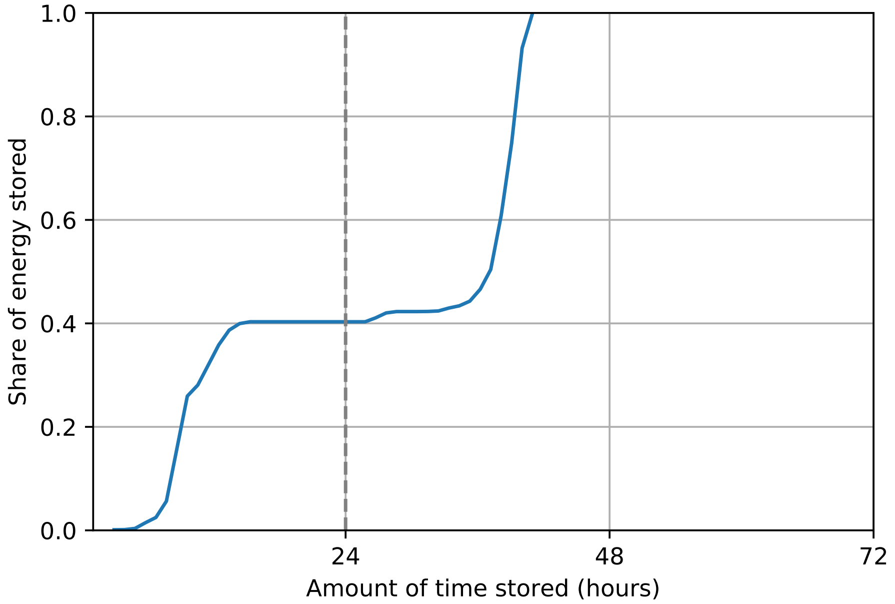
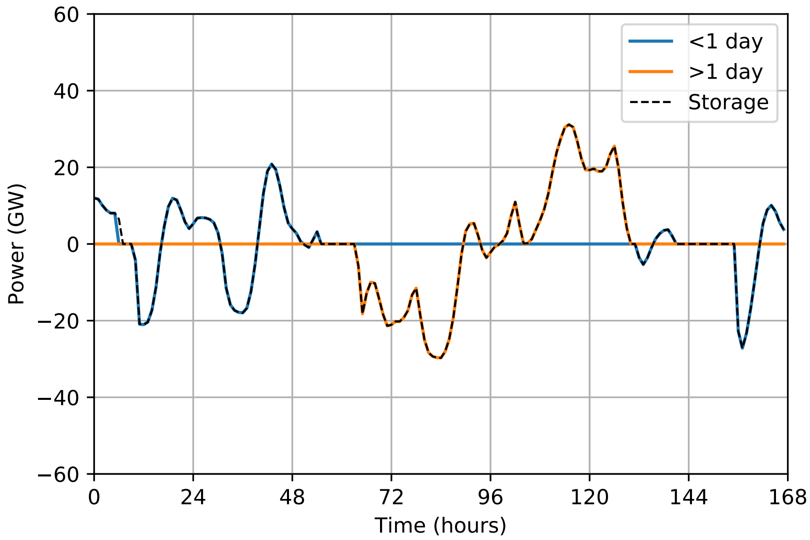


Figure 3.9: Share of energy shifted which is shifted by up to certain amounts of time, found using the FIFO method.

The minimum required size for each asset is the maximum value of the energy profile for each asset. In this example week, the daily or shorter storage asset would be 117 GWh and the longer timescale asset would be 480 GWh, as seen in Figure 3.10. In fact, in this example, the longer timescale storage assets needs to be the same size as the minimum overall storage size. This is not a problem because the overall storage size calculated using the method from Section 3.2.2 represents a minimum limit. If those overall needs were met using these storage assets operating using a FIFO principle, the aggregate storage size required would be larger than that minimum size.

One could use the same principle to find the discharging power required for each type of storage asset. Based on Figure 3.10, the daily or shorter asset would need to be able to discharge at 27.2 GW and the longer than daily storage asset would need 29.7 GW, if they were operated using this strategy. However, because assets of these sizes could be operated using several different strategies, these values do not necessarily represent the minimum discharging powers required for each type of resource.



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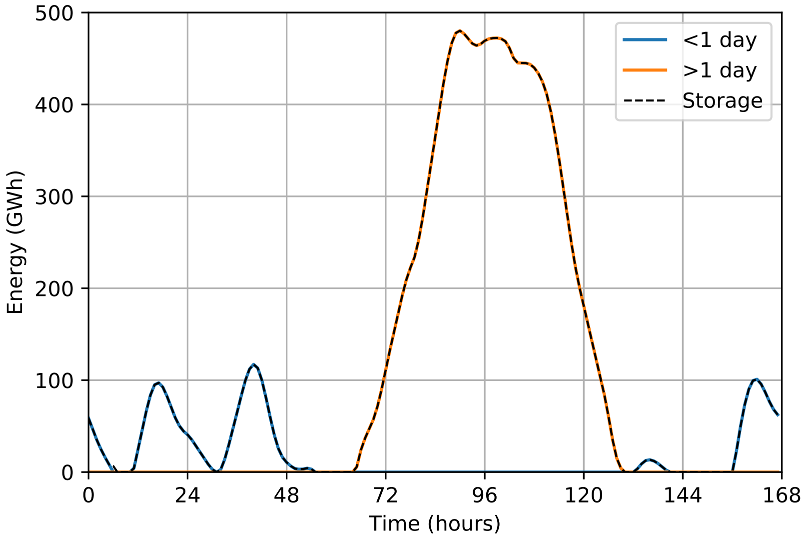

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Figure 3.10: Power and energy profiles for two storage assets which could meet the energy shifting requirements of the example week, found using the FIFO method. One asset can store energy for up to a day and the other can store energy for longer.

Using FIFO allows accounting for differences in efficiency, with some units being “lost" upon entering (charging efficiency), upon leaving (discharging efficiency), or over time while in the store (self-discharge). As with the overall storage, assuming perfectly efficient energy shifting means the analysis does not assume a particular set of devices is used to provide the energy shifting. This also yields the minimum possible size required and is therefore a very useful limit to understand. Less than perfect efficiency would require additional capacity to ensure all demand is met.

3.3.2 Last in first out (LIFO) method

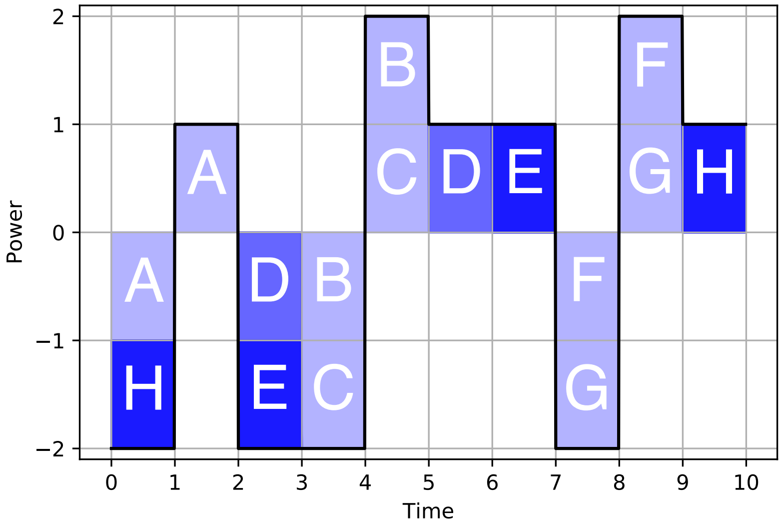
Last in first out (LIFO) algorithms are used to keep track of units of assets as they enter an leave a store or queue. In this case, those units are units of energy. This works well in the case of shifting energy through time, whether that is provided by traditional energy storage or shifting demand.

Like FIFO, the LIFO strategy enables calculating how long each unit of energy remained in storage before being used and therefore estimating the need to shift energy for different amounts of time; however, it discharges the most recently stored units of energy first. These units of energy could be allocated to different flexible resources based on their properties to create a portfolio of assets which could meet the overall energy shifting requirements of the system. This approach would maximize the amount of energy stored for the shortest possible durations, but some energy might remain in storage much longer.

The LIFO strategy is illustrated first on a stylized net load profile of ten time steps and then on the example week.

Figure 3.11 shows how LIFO would allocate the different units of energy in the stylized net load profile, with each unit of energy labeled with a letter when it is charged and discharged from the aggregate storage. Much more energy is stored for shorter amounts of time, with five units (A, B, C, F, and G) only shifted by one time step using LIFO, compared with only two units using FIFO.

Figure 3.12 shows the corresponding requirements of three types of resources, which can shift energy for one time step, two to three time steps, and four or more time steps. The required power and energy capacities of the LIFO one time step resource are twice as large as the one time step resource indicated using FIFO, although they account for more than twice as much energy. This indicates this method might be more suitable for places with many resources which operate



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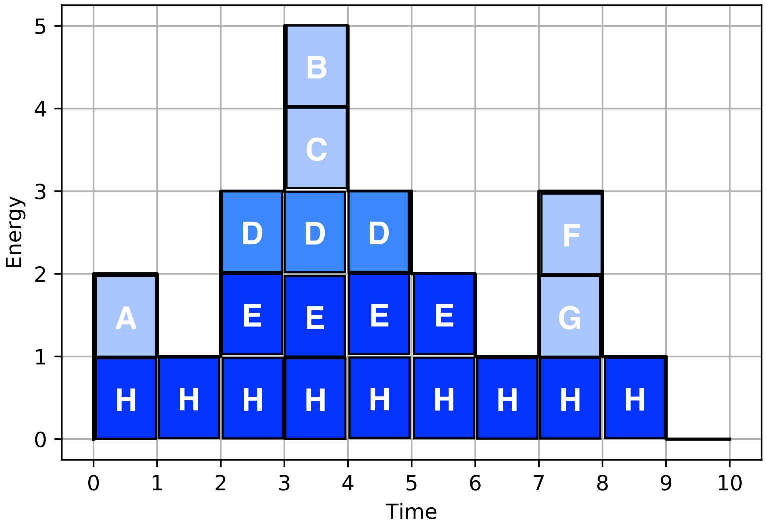

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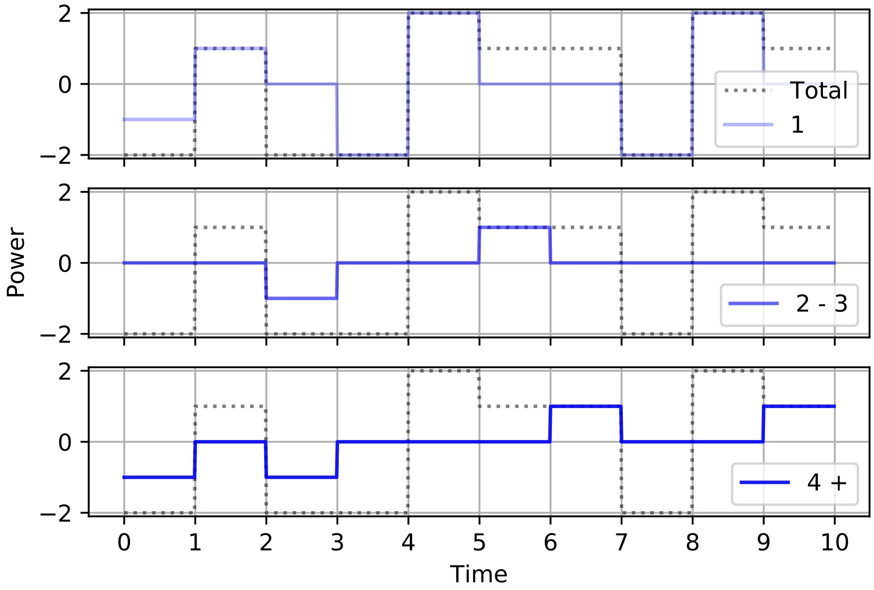
Figure 3.11: Illustration of last in first out (LIFO) method for stylized example net load profile. Each unit of energy is labeled with a letter when it is charged (power less than zero) and when it is discharged (power greater than zero). The darker colors signify units of energy which are stored for more time, while lighter colors are stored for less time.

over shorter timeframes with higher throughput, although this is investigated further in subsequent chapters.

The LIFO method is also applied to the example week to illustrate how it might operate on a more realistic net load profile. For consistency, the same daily cutoff point is used to illustrate how to approximate the necessary sizes of two different resources, one which could store energy for up to one day and one which could store



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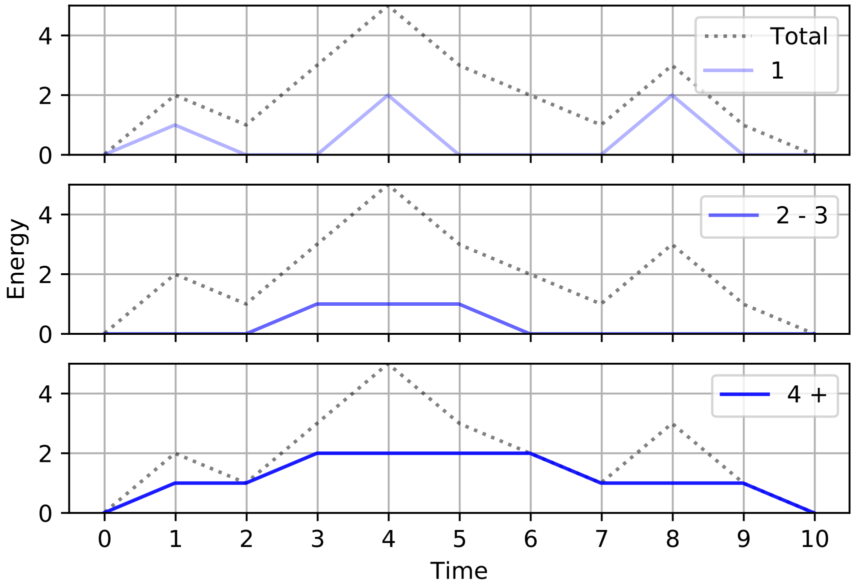

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Figure 3.12: Power and energy profiles for three flexibility resources which can shift energy for different amounts of time, created using LIFO to disaggregate overall energy shifting needs for the stylized example.

it for longer, based on how they might operate under the LIFO paradigm.

The minimum required size for each asset is the maximum value of the energy

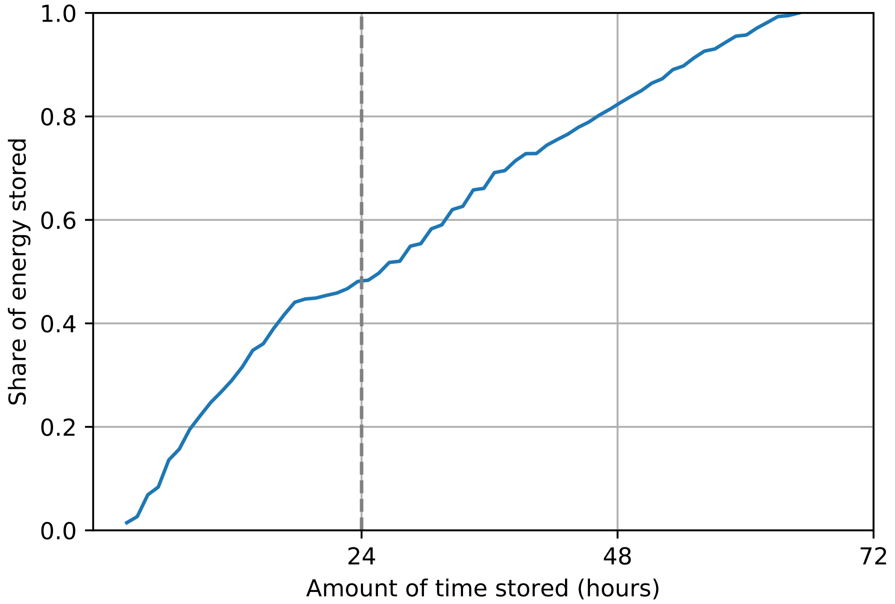
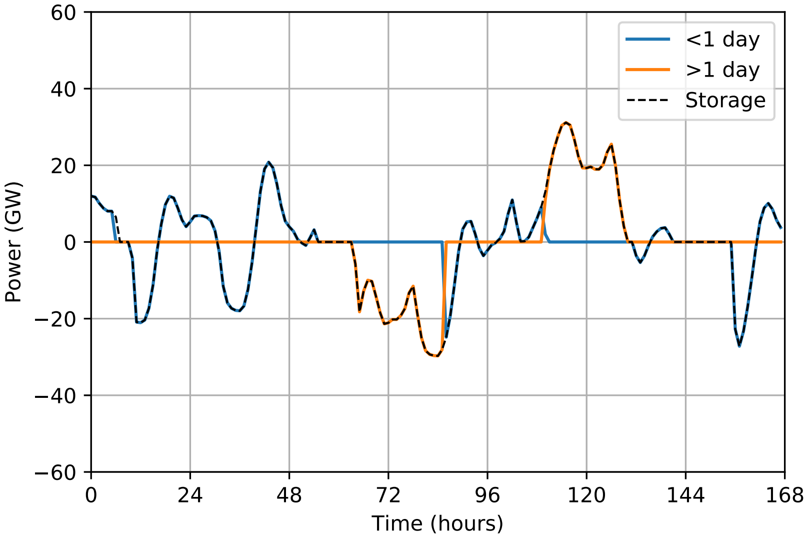


Figure 3.13: Share of energy shifted which is shifted by up to certain amounts of time, found using the LIFO method.

profile for each asset. In this example week, the daily or shorter storage asset would be 117 GWh and the longer timescale asset would be 423 GWh, as seen in Figure 3.14. These are both smaller than the minimum overall storage size required, because both resources are in use at the peak of the minimum overall storage profile. However, if those overall needs were met using these storage assets operating using a LIFO principle, adding together these two sizes means the aggregate storage size required would be slightly larger than the minimum overall capacity required.

One could use the same principle to find the discharging power required for each type of storage asset. Based on Figure 3.14, the daily or shorter asset would need 27.2 GW and the longer than daily storage asset would need 29.7 GW, if they were operated using this strategy. However, because assets of these sizes could be operated using several different strategies, these values do not necessarily represent the minimum discharging powers required for each type of resource.

Using LIFO allows accounting for differences in efficiency, with some units being “lost" upon entering (charging efficiency), upon leaving (discharging efficiency), or over time while in the store (self-discharge). As with the overall storage, assuming



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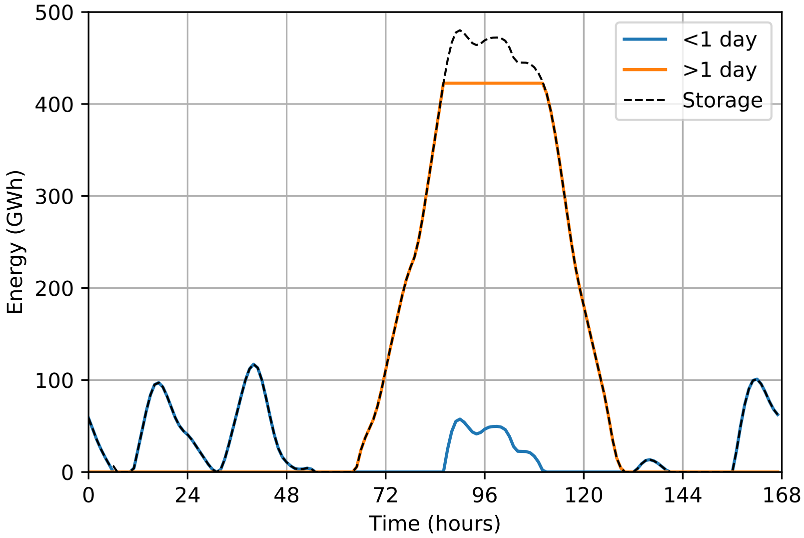

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Figure 3.14: Power and energy profiles for two storage assets which could meet the energy shifting requirements of the example week, found using the LIFO method. One asset can store energy for up to a day and the other can store energy for longer.

perfectly efficient energy shifting yields the minimum possible size required and is therefore a very useful limit to understand. Less than perfect efficiency would require additional capacity to ensure all demand is met.

3.3.3 Filter method

Bandpass filters are a standard way to identify components of a signal which correspond to a frequency range of interest. Filters can therefore be used to identify components of the aggregate storage profile with different frequencies of charge and discharge cycles. This corresponds to different amounts of time for which energy is stored. Therefore this method can help identify patterns in energy shifting needs.

For this application, the phase must be maintained to ensure the different profiles align properly in the time dimension. Therefore, it is necessary to process the data using both forward and backward filtering (for example, *filtfilt* in MATLAB or Python). This is possible because the whole time series is known and there is no need for real time filtering. Furthermore, the filters should be critically damped and results should not have significant overshoot. Based on these criteria, finite impulse response (FIR) filters were the most appropriate option.

These FIR filters can be applied to the overall storage profiles to identify components which correspond to any timeframe of interest, for example based on demand patterns or a particular technology's optimal cycling behavior.

To illustrate the application of this method, a daily filter is used for the example week. When there is a single cut-off frequency, rather than a band of frequencies of interest, either a high-pass or a low-pass filter can be used to identify components of interest. Figure 3.15 shows both high-pass and low-pass FIR filters which could be applied to the week-long example at hourly time resolution. In this example case with a relatively short sample length, the low-pass filter is much more specific to the daily frequency, so it makes more sense to filter out the signal components which are longer than one day and then subtract those from the overall signal. Although this filter preserves the phase, the absolute magnitude of the results may need to be adjusted by a constant to ensure the values make physical sense, for example shifting the energy profile upwards to avoid negative storage energy capacity or centering the net load around zero to ensure energy balance. Therefore, the magnitude of storage energy capacity is taken to be the difference between the maximum and minimum amplitudes.

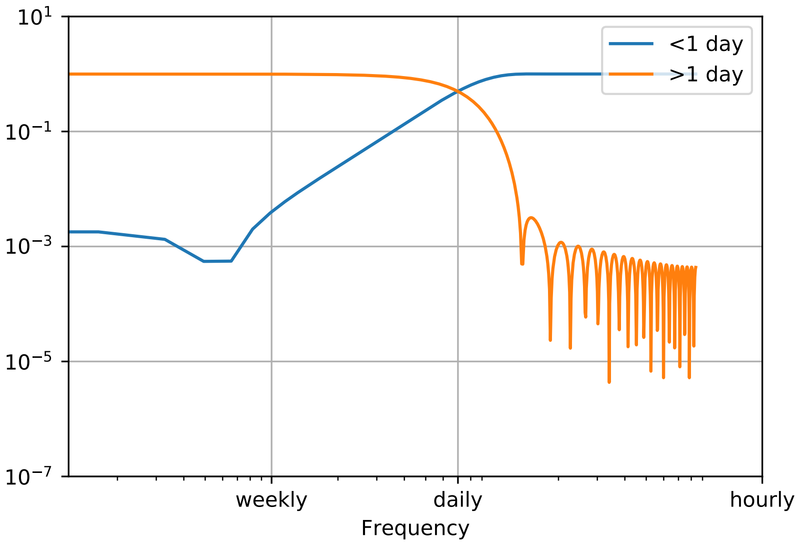

Figure 3.15: Highpass and lowpass FIR filters with a daily cutoff frequency.

Figure 3.16 shows the components of the storage power and energy profiles respectively which correspond to energy stored for up to one day and longer than one day. The minimum required size for each asset is the maximum value of the energy profile for each asset. In this example week, the daily or shorter storage asset would be 100 GWh and the longer timescale asset would be 475 GWh, as seen in Figure 3.16.

One could use the same principle to find the discharging power required for each type of storage asset. Based on Figure 3.16, the daily or shorter asset would need to be able to discharge at 17.6 GW and the longer than daily storage asset would need 21.6 GW, if they were operated using this strategy. However, because assets of these sizes could be operated using several different strategies, these values do not necessarily represent the minimum discharging powers required for each type of resource.

Interestingly, in Figure 3.16, there are a few times when one asset is charging and the other is discharging. This would imply that sometimes these assets actually charge or discharge into each other, rather than directly to meet demand. While it remains to be seen whether this strategy would make sense in reality, especially with less than perfect efficiency, this is not necessarily bad and could be beneficial as different assets operate not only over different timescales but also with different

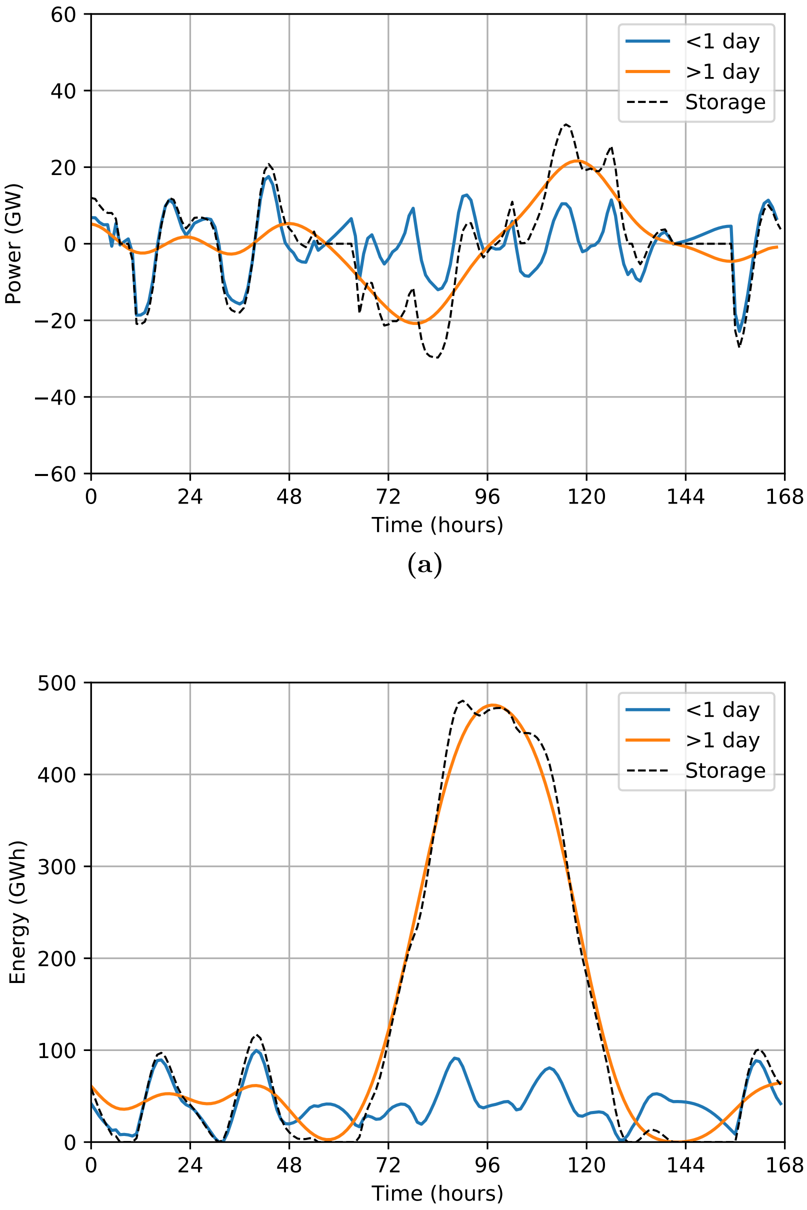

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Figure 3.16: Power and energy profiles for two storage assets which could meet the energy shifting requirements of the example week, found using the the filter method. One asset can store energy for up to a day and the other can store energy for longer.

ramp rates. Using them in conjunction could potentially help meet different sorts of flexibility requirements.

To determine particular frequency bands of interest for subsequent analysis on annual and multi-year-long profiles, demand and net load profiles were characterized

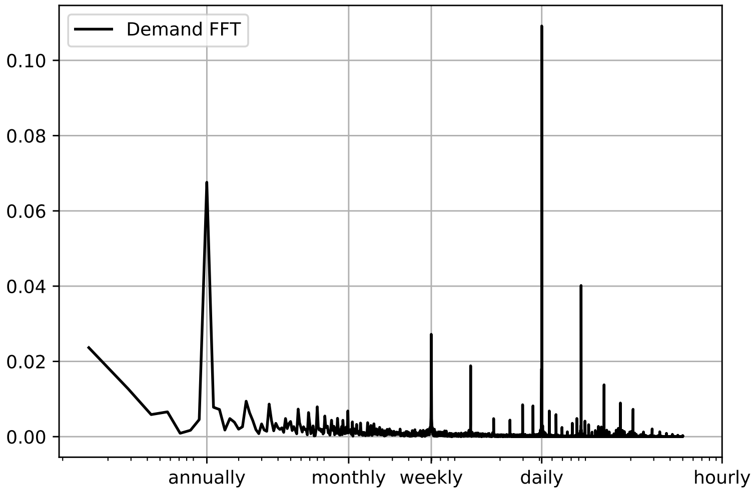


Figure 3.17: Fourier transform of electricity demand in Great Britain from 2009 to 2019 shows clear annual, weekly, daily, and 12-hourly patterns.

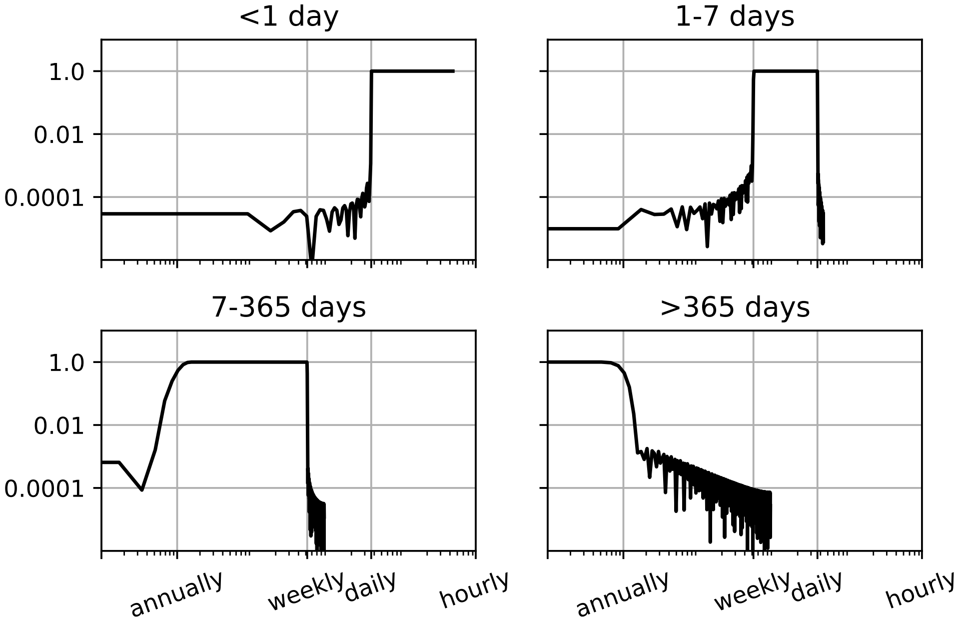


Figure 3.18: FIR filters corresponding to daily, weekly, annual, and longer frequencies can be applied to overall storage profiles

using Fourier transforms. Unsurprisingly, the largest spikes in Figure 3.17 correspond to daily, annual, 12-hourly, and weekly patterns in the demand profile. The daily, weekly, and annual limits were chosen for further analysis.

Figure 3.18 shows the FIR filters, designed using daily, weekly, and annual frequencies as cutoffs, which are used for analysis of multiyear profiles at hourly resolution in subsequent chapters. Filters could be designed for other timeframes and applied in the same way.

3.4 Flexible demand profiles

This section describes a method to create flexible demand profiles with different degrees of flexibility, to address the third sub-question of how to test the utility of different levels of degrees of flexibility.

The flexibility requirements will be met with a portfolio of different flexible resources. Some of these technologies currently exist, while others may be developed in the coming years to address this problem. For demand side resources in particular, there is significant uncertainty about the degree of flexibility which will be available in the future. Therefore, it is worthwhile to understand the effects of different degrees of demand side flexibility on the remaining system flexibility requirements.

To investigate how temporal flexibility requirements depend on demand patterns, scenarios with additional demand from electric vehicles (EV) and electric heating are used. Because there is significant uncertainty about future electricity demand and how flexibility it might be, there is value in investigating how the degree of flexibility might affect any remaining system flexibility needs.

One could quantify the temporal dimension of demand flexibility by the amount of time the electricity use is displaced from when it would have been originally demanded. Inflexible EV and electric heating profiles can be taken as the original counterfactual. Flexible demand profiles can be generated which allow a certain degree of shifting this demand away from the inflexible profile to satisfy a particular objective, in this case flattening the net load.

The amount of demand available to be shifted and the amount of time by which the demand is displaced can both be varied to test the effects of different degrees of flexibility on the remaining energy shifting needs.

3.4.1 Flexible profile creation method selection

This section presents a method to create load profiles for flexible demand side resources, based on the net load, a counterfactual inflexible load profile, and the degree of flexibility of the demand side resources at each time step. This is only one method for creating flexible demand profiles for electric heating and EVs. The aim here is only to generate a credible aggregate flexible demand profile, from which one can then analyze remaining system flexibility requirements. The aim here is not to explore different options for flexible demand side resource utilization, objectives for flexibility use, dispatch strategies, or control algorithms for smart devices, which are discussed more in Chapter 2.

The method presented here focuses on creating a flexible profile for each demand side resource, if the energy were flexible up to a certain amount of time displaced from when it would have been originally demanded. This method enables testing the effects of different degrees of flexibility and characterizing the benefits of being flexible to displace the energy use further in time from ideal demand time.

The objective for flexible profile creation is net load flattening. This is a well established principle, to lessen steep ramping rates and avoid needing peaking plants for additionally marginal generation. Crucially, the net load is used, rather than the load profile, which ensures the excess renewable supply is utilized when it is available. In practice, this load flattening is net load trough filling as the baseline demand is not flexible.

Other criteria and objectives for flexibility use could be selected, for example, minimizing costs, greenhouse gas emissions, renewable curtailment, or storage size required. These were not selected, due to the need for additional data, the introduction of further assumptions, and the desire to focus on the temporal and technical dimensions of flexibility requirements while remaining agnostic to the technologies which would provide these flexibility services.

3.4.2 Flexible demand side resource profile creation

The flexible demand profiles are created by adjusting the inflexible demand profiles for each resource. The inflexible demand profile for each resource is taken as the counterfactual or ideal demand profile from which end users could potential be flexible. To illustrate the method, the inflexible EV charging profiles from Crozier et al. [107, 108] are used; however, it could in principle be applied to any inflexible demand side resource profile, including other inflexible EV charging profiles or inflexible heating demand profiles.

To begin, the correct net load profile must be selected. The generation must be sized correctly, such that enough energy is generated over the entire time horizon to meet the original demand and the additional demand from the flexible resource. However, this supply should be subtracted from only the original demand profile, so that the remaining demand can be flexibly distributed to fill troughs within set constraints. Figure 3.19 shows how the net load profile is adjusted when adding in the additional generation to account for the energy which will be used by the flexible demand side resources.

The availability and degree of flexibility of the demand side resources must be known. This is measured here by how much time they could shift demand away from when it would have been demanded, measured by the inflexible demand profile. To illustrate this method, electric vehicle charging is assumed to be flexible up to twelve hours on either side of the inflexible demand. One could also use an asymmetrical flexibility window or a fixed flexibility availability profile, where some hours are inflexible or are flexible to different degrees. In subsequent chapters, different flexible window sizes are used to test the effects of the degree of flexibility of the demand side resources on the remaining temporal flexibility requirements.

The profile creation algorithm loops through the net load and inflexible demand profiles. At each time step, there is a specific amount of inflexible demand. Around that time step, there is a window in which that demand could be flexible. The amount energy demanded at the time step could be redistributed throughout that flexible window, such that it flattens the net load, by filling in the troughs and

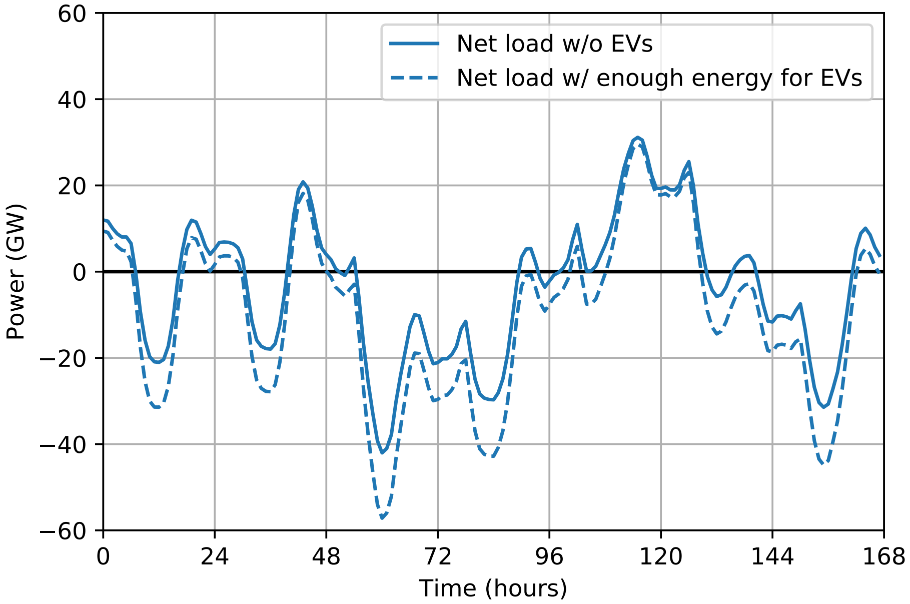


Figure 3.19: Net load profile with enough supply to account for electricity demand from charging electric vehicles but without additional demand yet added. Note different vertical axis scales.

not adding to the peaks. The net load flattening algorithm is solved at each time step for each window with a rolling time horizon; it does not solve each window simultaneously. Figure 3.20 shows how the algorithm redistributes the flexible EV demand within each window over a rolling time horizon, for five time-steps. Because this redistributes the energy within the time horizon by filling from the net load minimum within each window, the resulting aggregate flexible demand profile should be a global optimum solution which respects the constraints. Starting at a different time-step or going the other direction through the profile might produce different outcomes for individual EVs but should produce the same aggregate profile.

Figure 3.21 shows the net load profiles with the inflexible demand added, with the demand allocated flexibly within the flexible windows assumed, and with the additional demand yet to be added. The resulting demand profiles for the flexible resources are shown in Figure 3.21.

Crozier et al. [109] show that smart flexible EV charging which respects individual vehicle travel and battery constraints could effectively fill troughs in the

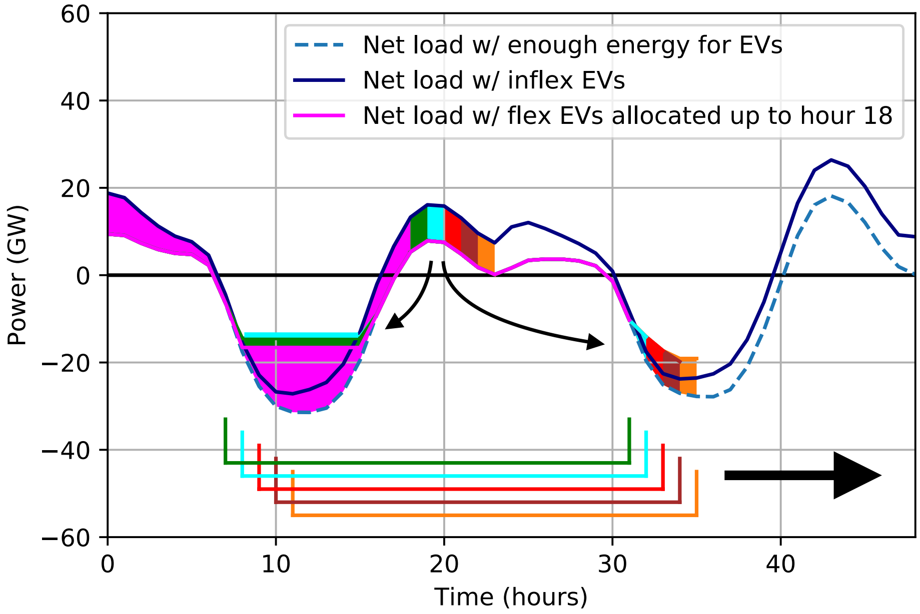
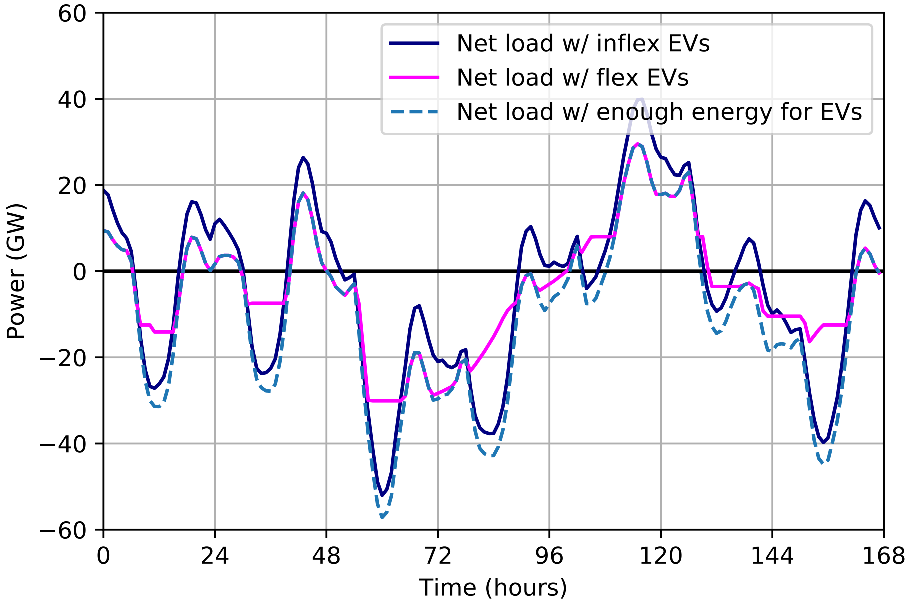


Figure 3.20: The aggregate flexible EV charging profile is created by using a rolling time horizon with a window up to 12 hours on either side of original inflexible charging demand to redistribute the demand and flatten the net load. For hours 18-22, each time-step is color coded to show the energy originally demanded if EVs were charged inflexibly, the window in which the load flattening problem is applied, and the timing of the flexible EV charging demand.

daily load profile without increasing peak power demand. Therefore, it is reasonable to assume that there are viable smart charging options which could create the aggregate EV charging profile from the method developed here while respecting travel and battery constraints, at least for demand flexible up to 12 hours, although the method developed here does not consider these individual vehicle constraints.

Due to the scale of this problem at national or regional level and assumptions about aggregate flexibility, it is acceptable to simply redistribute the aggregated energy at each time step independently, without considering the shape of a particular device power profile.

As described in Chapter 2, others have shown feedback and knock-on effects, especially for flexible heating or other thermostatic loads as they later adjust to remain within their temperature bounds. However, this method does not ask all devices to respond at the same time or in the same way, but rather to respond in such as way that the aggregate demand profile could fill troughs in the net load. This could



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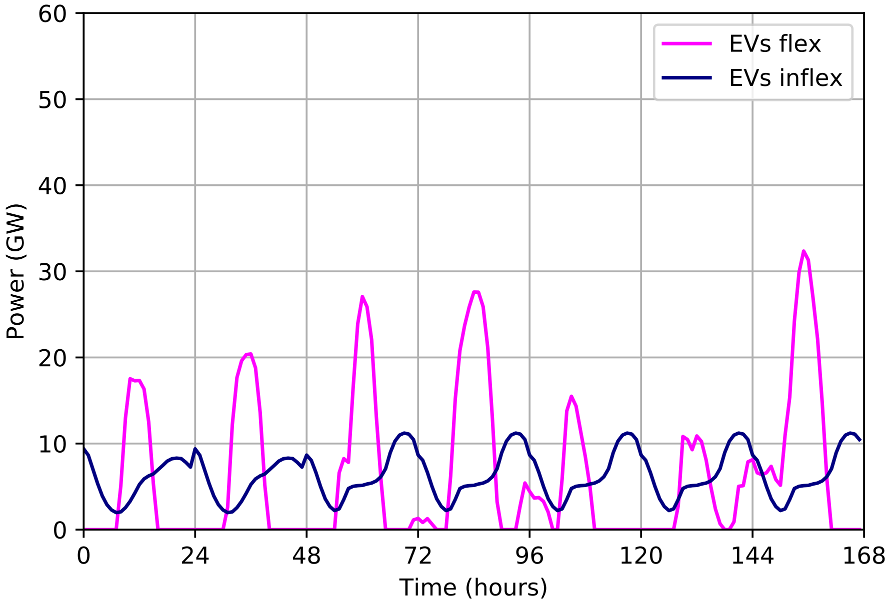

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Figure 3.21: Net load profiles with flexible and inflexible EVs (above) and EV demand profiles (below), where flexible EV demand is profile is created from charging electric vehicles flexibly up to 12 hours on either side of original inflexible charging demand.

be achieved and feedback effects mitigated with heterogeneous device characteristics and appropriate control algorithms. Furthermore, the analysis tests several different sizes of possible windows, so the goal is more to show the potential effects on remaining flexibility needs if the devices could be flexible up to a certain point, rather than to replicate specific device behavior, either individually or in aggregate.

3.5 Key takeaways

This chapter addresses the question of how to characterize flexibility requirements over different timescales in electricity systems with high penetrations of variable renewables. To do this, it develops methods which can be used to address the following problems.

1. How can overall temporal flexibility requirements be characterized?
2. How can flexibility requirements at different timescales be identified?
3. How can the utility of different levels of demand flexibility be tested?

System flexibility requirements can be characterized in terms of the total energy capacity and power capacity required for all flexibility resources in the system. The overall need to shift energy through time can be quantified and approximated by treating this energy shifting as an aggregate storage device. The energy and power capacities of this hypothetical overall storage device can be used to quantify the need for aggregate flexibility resources to shift energy through time.

It is useful to investigate not only the amounts of energy which must be displaced in time, but the different timescales involved in this energy shifting. Shifting energy over hours could require different flexibility resources from shifting energy over weeks. Breaking down the overall flexibility requirements into different timescales, based on the amount of time energy would be stored or shifted for, can inform which flexibility resources might be most appropriate or most needed in different contexts.

The novel application of three different methods is proposed to address the problem of disaggregating flexibility requirements over short-, medium-, and long-term timescales. These three disaggregation strategies are used to create a portfolio of flexibility resources which could meet demand in highly renewable energy systems.

The timescale breakdowns and corresponding flexible resource portfolios produced using these strategies are all plausible and would meet all demand, but are not necessarily realistic or optimal from a cost or emissions perspective. However, they are still very useful tools to understand the range of possible energy shifting timescales required and, most importantly, enable studying how short-, medium-, and long-term flexibility requirements depend on system configuration, generation mix, and demand patterns. In particular, by comparing results achieved using the different strategies, one can investigate which trends hold across portfolios regardless of strategy and could therefore be considered when making planning and investment decisions.

Any insights from results will only be as good as the data inputs, but the methods are versatile and could theoretically be applied to any set of input demand and supply data. Significant changes to weather profiles (e.g. due to climate change [110]) or to electricity demand (e.g. due to electrification of heating [111] and transportation [109, 112] or to changes in behaviors and social practices [113, 114]) could affect the need for flexibility and are an important area of further research.

In subsequent chapters, these methods are applied to the case study of Great Britain and used to examine the effects of generation mix, system configuration, and demand patterns on flexibility requirements over different timescales.

4

Estimating flexibility requirements of a fully renewable and highly electrified Great Britain

This chapter presents temporal flexibility requirements for a future Great Britain powered by variable renewable energy, under a potential future scenario with significant decarbonization through electrification. It addresses the question of how much energy future electricity systems would need to shift through time and by how much time. The results are presented for a potential future scenario, with only wind and solar power and with demand based off of assumptions from the National Grid Future Electricity Scenarios (FES) [2]. The analyses in subsequent chapters investigates the sensitivity to these assumptions to show how varying generation mix and demand could affect the need to shift energy over different timescales and therefore the capacity required for flexible resources to accomplish this shifting.

In the rest of this chapter, Section 4.1 describes the data and model inputs used; Section 4.2 describes the details and assumptions of the case study; Section 4.3 presents the overall temporal flexibility requirements for these scenarios; and Section 4.4 shows how these flexibility requirements can be broken into the need for flexibility over different time horizons.

4.1 Data and model inputs

These methods rely on realistic or representative data inputs to ensure meaningful results and insights. This section describes the data sources and processing used for the Great Britain case study.

4.1.1 Solar and wind generation

Renewable generation profiles are calculated from hourly capacity factors for wind [115] and solar photovoltaics (PV) [116], based on historical weather data from 1980 through 2016. Figure 4.1 shows these hourly capacity profile factors for each year and the mean over the 37 year period.

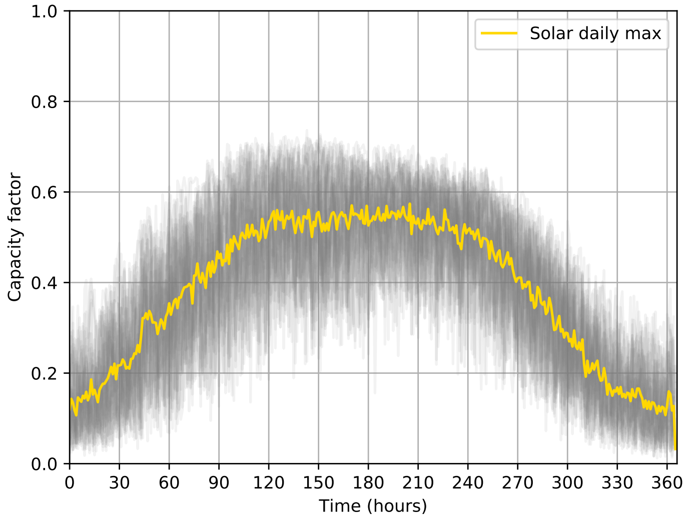
Using historical data for wind and solar generation profiles was considered and initial analyses were completed using these data. This would have been consistent with demand data, all from the same official public source and at five minute resolution. However, these supply profiles were wind and solar generation and did not include any historical curtailment.

For this analysis, it is important to use profiles which represent the potential available generation from these sources, as that power would not necessarily be curtailed in a more renewables dominated scenario. Therefore, data which capture the full potential at all times were required.

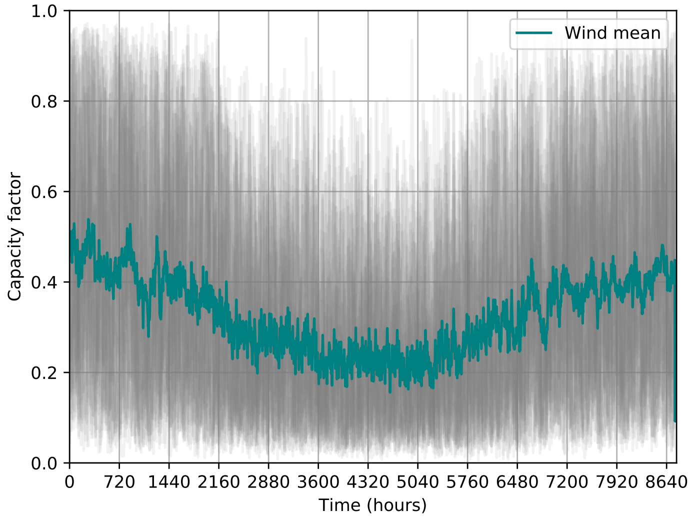
The hourly capacity factor profiles chosen for use are based on reanalysis of satellite weather data from Staffell and Pfenniger, the team behind renewables.ninja [115, 116], ensuring they represented all available potential. These were publicly available, with the assumptions and results validated and publishes in the literature.

The hourly time resolution means that requirements for sub-hourly flexibility are not included in the scope of this study. Although timescales for energy shifting of less than one hour were not considered due to the limitations of the data available, the methods described could be applied to much higher temporal resolution data if available.

Using many years of historical data ensures the analysis accounts for variation in demand and weather patterns across years and enables analysis of long term-tern



(a)



(b)

Figure 4.1: Historical solar and wind capacity factors for Great Britain since 1980. The colored solar profile represents the mean daily maximum capacity factor. The colored wind profile represents the mean capacity factor at each hour.

flexibility requirements. However, it must be recognized that this historical data may not cover worst case scenarios or be representative of future patterns, and may miss some longer term trends.

The option of using climate models to generate future weather patterns and therefore renewable generation capacity factor series was explored but is considered beyond the scope of this work. Climate change will likely continue to alter weather patterns, including potentially affecting the solar and wind potential. However, due to data constraints and the significant uncertainty about the specific effects, effects due to climate change on solar and wind profiles were not considered. This is a potentially important area of future work and the methods developed here could be applied to updated profiles.

4.1.2 Demand

Demand is based on recent historical electricity demand profiles. For some future scenarios, additional electricity demand from potential electrification of heating and vehicles is included, as described in Sections 4.1.4 and 4.1.5.

Data sources

Recent historical demand data was available at at five minute resolution from 2009 to 2019 from Elexon Balancing Mechanism Reports [117], shown in Figure 4.2. This demand data is the sum of generation data, but the transmission network does not see embedded generation, include solar PV generation. To get a better estimate of demand, solar PV generation was added for 2013-2019 based on estimates from Sheffield Solar PV Live [118], with solar PV generation data before 2013 unavailable and considered negligible. Data from the year 2020 was not included due to the significant changes in demand due to the ongoing COVID-19 pandemic and associated social restrictions. Although examining effects of such changes in demand patterns could be an interesting avenue for further analysis, it is beyond the scope of this research.

Data cleaning

These data were relatively high quality, but still required some data cleaning to address some missing or unrealistic values. The original demand data were publicly available at five minute resolution and all data cleaning was done at this temporal resolution. These cleaning processes were originally developed and completed on

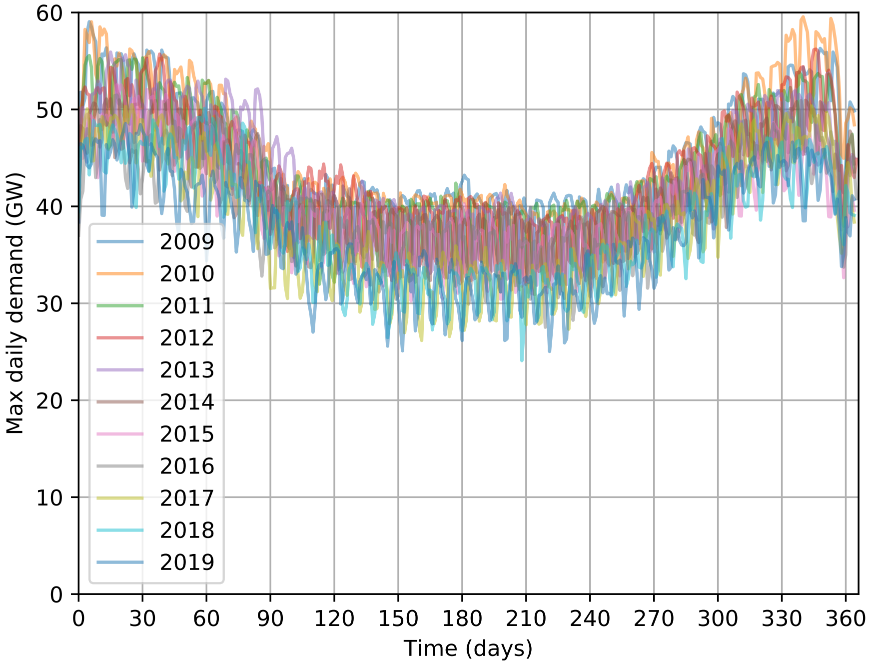
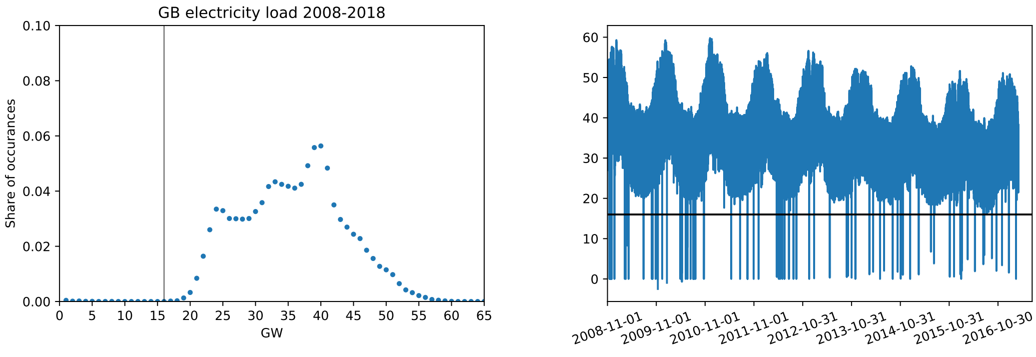


Figure 4.2: Recent historical electricity demand in Great Britain, daily maximum.

data from the years until 2016 and then subsequently repeated as more data from more recent years became available.



(a) **(b)**

Figure 4.3: The lower limit for realistic electricity load data for Great Britain was set at 16 GW based on historical data.

The profiles were screened for unrealistic values and these were removed from the dataset. The upper limit for demand was taken to be 61700 MW, which is the highest load reported by the UK government since 1920 [119]. The lower limit for electricity demand was set at 16000 MW, which was chosen based on recent historical demand profiles, shown in Figure 4.3.

Duplicate or multiple entries at a single time step were removed. When the there was a gap immediately followed by a duplicate (or vice versa), the extra value was used to fill the gap. If the values were not the same despite having the same timestamp, the immediately surrounding time window was screened for missing values. If the entries were identical at every value, then one copy was simply dropped. Otherwise, the value which created a smoother gradient between the two surrounding points was kept and the other was dropped.

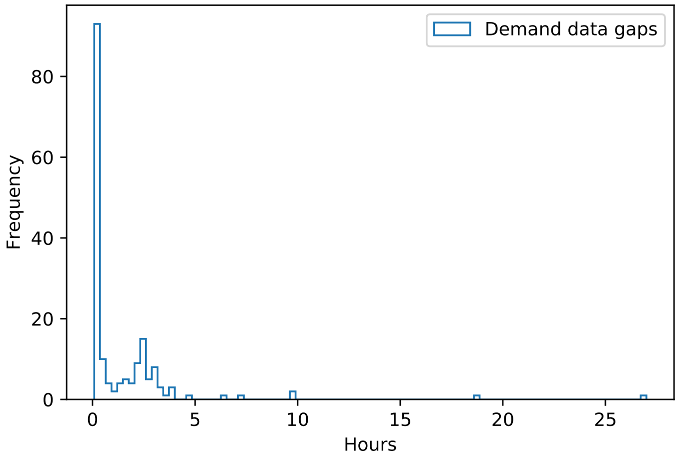


Figure 4.4: Distribution of lengths of gaps with missing data in GB demand profile.

The gaps, from originally missing data or removed during data cleaning, were addressed in two ways. The overwhelming majority of data gaps were single missing values, with a few longer stretches that needed to be filled, as shown in Figure 4.4 for the demand profile. For short gaps, of less than six hours, a linear interpolation was used. For longer gaps, data from a nearby day (within a week on either side) was chosen to fit in smoothly with the surrounding profile, as shown in Figure 4.5.

4.1.3 Generation and demand profile creation

For most analyses in subsequent chapters, the analysis is carried out over eight year time horizons. This was chosen based on the overlapping years in the availability of

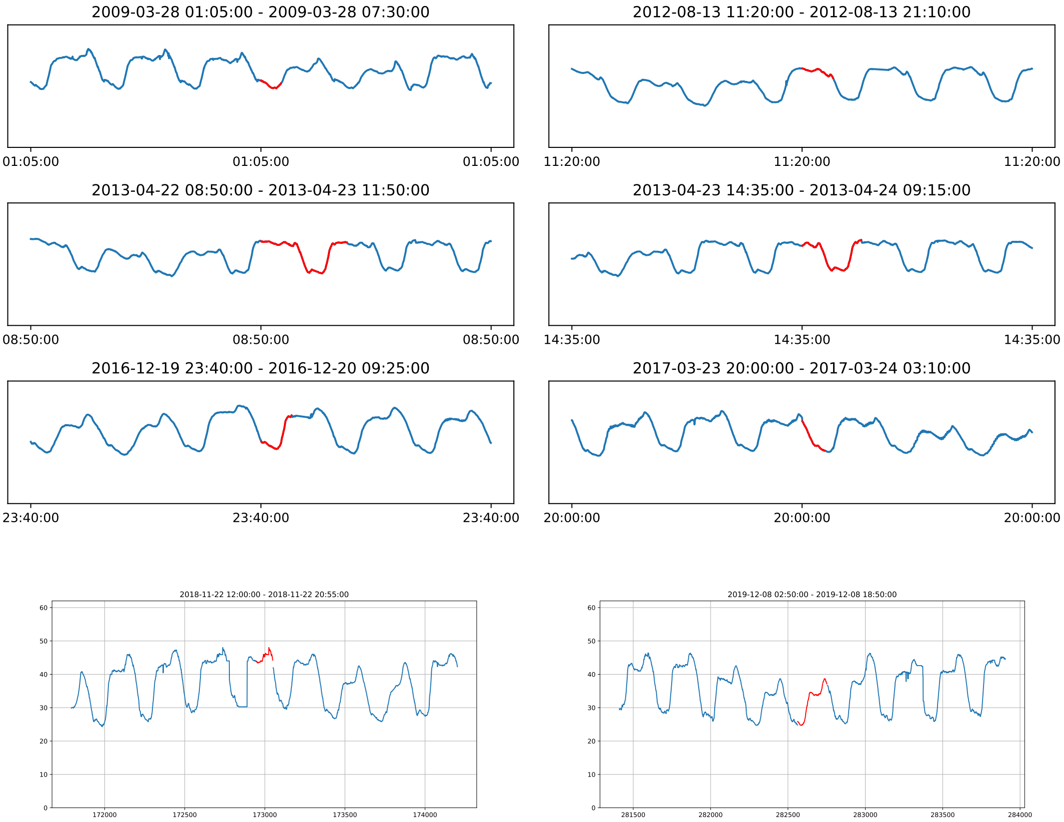


Figure 4.5: The demand profile with data gaps longer than six hours (blue) and the data from a nearby day used to fill in the gap (red).

demand and supply data, as demand is often correlated with weather patterns.

To investigate simulations with longer time horizons, and given the availability of multiple decades of weather data, a few options for creating credible longer demand profiles were explored. These are discussed further in the Appendix A.

4.1.4 Electric heating

To investigate potential effects of electrification of heating on flexibility requirements, potential electric heating profiles were generated and added to demand, before calculating the required generation, net load, and flexibility resource capacity requirements. There is significant uncertainty about the future of electric heating [120]. This uncertainty covers how much decarbonization will take place through electrification, the technologies which would be used to do so, the associated demand profile shapes, and how flexible this heating demand might be. This research does not aim to cover the breadth of this uncertainty, but rather to describe methods which could be applied to investigate effects of additional electric heating demand, both inflexible and flexible, on system flexibility requirements. For this analysis, heating profiles based on methods and assumptions from Watson et al. [111] have been used, but the general methodology could be applied using other electric heat demand profiles.

Selecting electric heat demand profile

When evaluating which profiles were most appropriate for this application, selection criteria included geographic coverage and resolution, temporal resolution, assumptions used, scalability, and availability of data or model to generate profiles.

Only heating profiles for Great Britain or models which have been validated for Great Britain were considered, given the relevance of building stock characteristics and social patterns for heating demand. Due to the national level of the analyses here, national level geographic coverage was required. Some profiles were available at higher spatial resolution and these could be aggregated using population weighted averages to create an improved national profile. For profiles at the building or household level, it was important that these were based on data representative of the wider national building stock to ensure that scaling them would yield reasonable national profiles.

The ideal heating demand profile would have data with at least hourly resolution, to align with the temporal resolution of the supply data. Although some with up to daily temporal resolution were considered, this was not chosen given the availability of higher temporal resolution options which met other criteria. Profiles with finer than hourly resolution data could be useful, but this was not a deciding factor because they provided no advantage for this case study given the limitations of the hourly solar and wind capacity factor data.

The profile would need to scalable to enable testing scenarios with different levels of electrification. To ensure scalability, one option would be a profile which accounts for heating demand directly and is agnostic to the technology providing that service. For example, this could be done by using outdoor temperature and building characteristics to calculating heating degree days and heating demand or by using historical gas demand and information about technologies used to reverse calculate demand for heat. Another option would be to use an option from literature which reports results for a particular technology and gives profiles either at a specific penetration level for the nation or at the household level, both of which could be scaled.

Profiles based on outdoor temperature, especially those which could be updated with new temperature profiles, were preferred over those based on historical gas demand. This is because of the potential for climate change to significantly change outdoor temperature and weather patterns, and therefore to affect the demand for heating, in the coming decades. The demand for heating can be expected to change certainly by the time electric heating were to be deployed more widely or the generation mix were to be more heavily dominated by wind and solar, if either were to occur in future.

For these reasons, the updated Watson et al. [111] profiles, which incorporate data from real world heat pump deployment to update a previously published set of heat demand profiles [121], were selected. These half-hourly household level profiles are available for selected temperature bands and different mixes of ground source and air source heat pumps. Their base case, with a 25% ground source and 75% air source heat pump mix, was also used as the base case for analysis here. To translate heat demand into electricity demand, the coefficient of performance (COP) for all heat pumps was assumed to be 2.5.

These household level profiles can be scaled up to account for different penetrations of domestic electric heating, but they cannot be used to account for commercial or industrial heating. However, this is sufficient to begin to investigate the potential impact of electrifying heating on flexibility requirements and the subsequent methods could be employed with other heating profiles as needed.

The Appendix A includes information about some work to create heating demand profiles from first principles, using historical temperature data, heating degree days, and assumptions about building characteristics. However, given the high degree of assumptions required and the availability of credible profiles from elsewhere, this work was ultimately not used for the analysis.

Temperature data inputs

The Watson et al. demand pump profiles require inputs of outdoor temperature data. These temperature data were sourced from the MERRA-2 dataset [104] and available at hourly temporal resolution and 0.5 by 0.625 degrees spatial resolution from NASA.

For the national level analysis, a national temperature profile was created using a population-weighted average, but one could easily create regional level profiles using the same methodology. Population weighting was chosen over area weighting because it would correspond better with energy demand. The population data for Great Britain were from a gridded population dataset based on the most recent UK census [122]. This method would work equally well if other temperature data were available, for example from future years or from climate change simulations to predict future demand.

Using climate models to understand future temperature patterns and inform future needs for heating and cooling was explored, but as with the solar and wind patterns, considered outside the scope of this work. The Appendix A contains some initial analysis of changes to heating and cooling demand under 1.5 C and 2 C scenarios.

Adding electric heating into analysis

An example electric heating profile is shown for a week in Figure 4.6, for a scenario where 100% of domestic heating is electrified via heat pumps. This electric heating demand profile is created using the historical temperature data from that example week and the Watson et al. [111] heat demand model. The profile magnitude could be scaled to study different penetrations of heating electrification.

This inflexible heating demand is added to the baseline demand when sizing the solar and wind generation capacity and creating the net load profile for subsequent

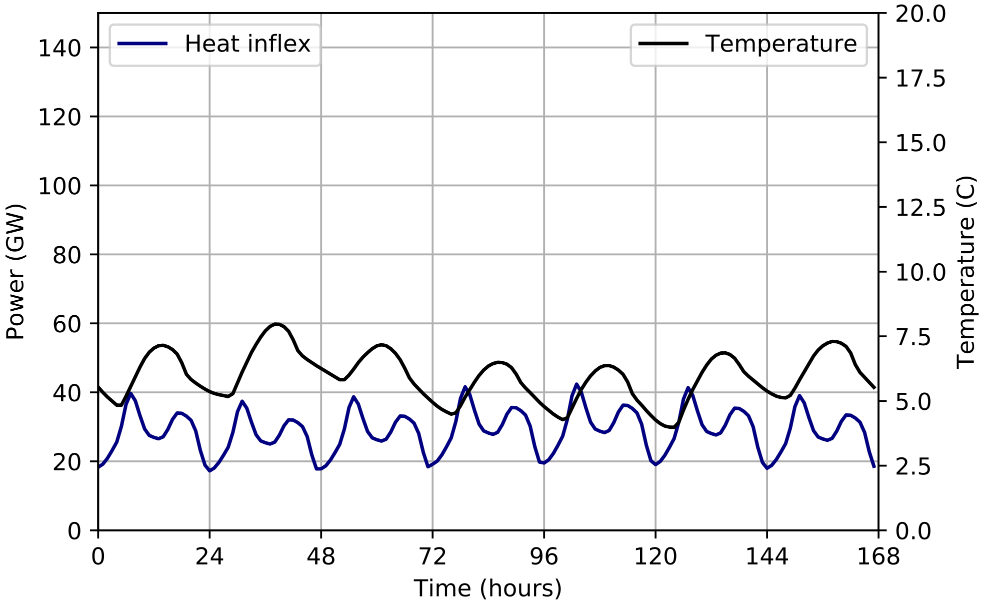


Figure 4.6: Electric heating demand profile based on Watson et al. [111].

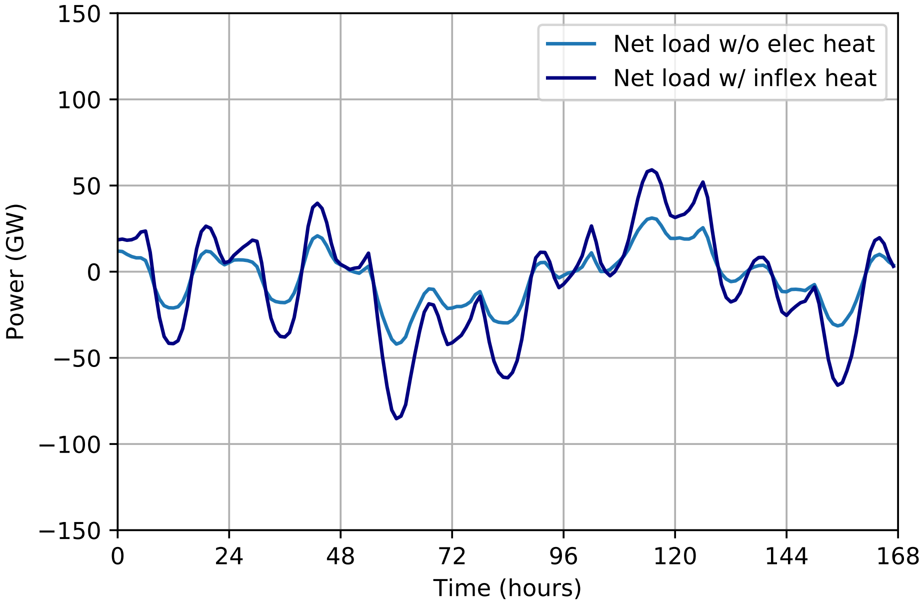


Figure 4.7: Net load profiles with and without inflexible electric heat pumps.

analysis. Figure 4.7 shows the net load profiles for the example week both with and without inflexible electric heating.

To study the effects of flexible heating on remaining flexibility requirements, a flexible electric heat demand profile can be created based on the net load and the inflexible heat demand profile. The methodology used is described in Chapter 3.

4.1.5 Electric vehicles

To investigate potential effects of electrification of transportation on flexibility requirements, potential electric vehicle charging profiles were generated and added to demand, before calculating the required generation, net load, and flexibility resource capacity requirements. Although vehicle electrification is a rapidly increasing trend, there is still much uncertainty surrounding the future of electric vehicles, including how much decarbonization will take place through electrification, how flexible vehicle charging might be, whether electric vehicles might be used for vehicle-to-grid services, and how transportation patterns may change in future. This research does not aim to investigate these uncertainties, but rather to demonstrate how one could evaluate the impact of additional demand from electric vehicles, both inflexible and flexible, on flexibility requirements. For this analysis, electric vehicle charging profiles based on methods and assumptions from Crozier et al. [107] have been used, but the general methodology could be applied using other electric vehicle charging demand profiles.

Selecting electric vehicle charging demand profile

Several criteria were important when selecting electric vehicle profiles for use in this analysis, including temporal resolution, geographic coverage, model and scenario assumptions, and data availability.

For this application and this case study, the EV profiles should be specific to Great Britain, as driving patterns are highly location dependent and context specific. If these methods were to be applied to other locations, one would need to use different EV charging profiles generated for that reason. These could possibly be generated from the same vehicle model, if one had different input data about transportation patterns.

Due to the hourly solar and wind capacity factor profiles used for this case study, the temporal resolution of the data was required to be at least hourly. Higher temporal resolution EV data would be an advantage if one had access to higher resolution supply profile time series.

This research assumes that transportation patterns remain broadly similar to current vehicle use in Great Britain and that private EV drivers would use cars similarly to how they use their internal combustion engine vehicles now. This is a reasonable assumption which allows initial investigation of the potential effects of additional demand from EVs on flexibility requirements. Furthermore, the methods described here can be implemented with other EV profiles, if one wanted to test other assumptions or had additional insight into how transportation patterns might shift in future.

Based on these criteria, EV profiles generated using UK national travel survey data and an electric vehicle model from Crozier et al. [107] were selected. These minute-resolution day-long profiles were specific to the UK, with typical profiles for each of the four seasons and different profiles for weekdays and weekend days. The baseline inflexible demand was taken to be Crozier's "uncontrolled" charging profile, which assumed home charging starting after the final vehicle journey of the day. For flexible charging profiles, this research applied the same objective of load flattening used in Crozier et al.'s "controlled" charging profiles; however, this was applied to the net load and is described further in Chapter 3.

Adding electric vehicle charging into analysis

An example inflexible EV charging profile is shown for the example week in Figure 4.8. This EV charging profile is created for the example week using the methodology and assumptions from the Crozier et al. [107] vehicle model.

This inflexible EV charging profile is created from Crozier et al.'s daily uncontrolled profiles. For each day, the appropriate EV charging profile is selected based on the season and day of week. These profiles are then joined together to create a single time series and resampled at the correct temporal resolution, in this case hourly.

This inflexible EV demand is added to the baseline demand when sizing the solar and wind generation capacity and creating the net load profile for subsequent analysis. Figure 4.9 shows the net load profiles for the example week both with and without inflexible EV charging.

To study the effects of flexible EV charging on remaining flexibility requirements, flexible EV charging demand profiles can be created based on the net load and the inflexible charging demand profile. The methodology used is described in Section 3.4.

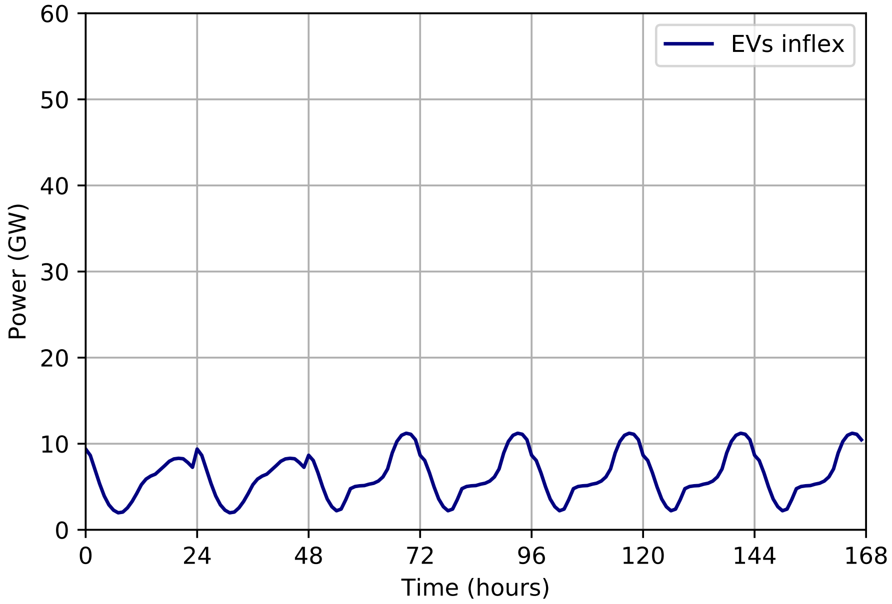


Figure 4.8: Inflexible electric vehicle charging profile based on Crozier et al. [107].

4.2 Great Britain case description

This section describes the details, assumptions, and data sources used for the base case which are used to understand temporal flexibility requirements in renewables-dominated, highly electrified scenarios.

4.2.1 Demand

The baseline electricity demand is based off of historical demand profiles, with an average of 307 TWh/year. This is demanded throughout the year with clear

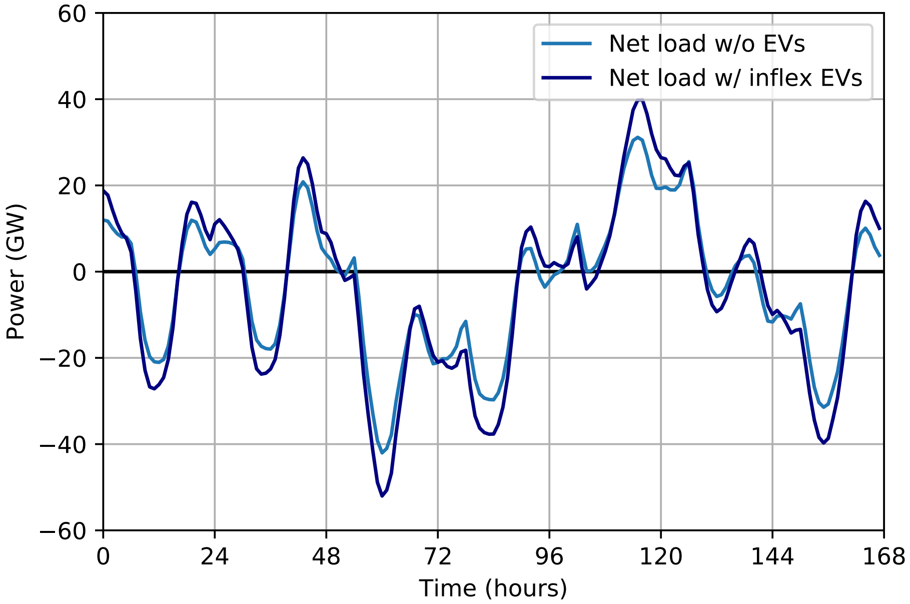


Figure 4.9: Net load profiles with and without inflexible electric vehicles.

seasonal variation, shown in Figure 4.10. It is worth noting that the total annual energy and peak power demand has been decreasing in GB over the past decade. There is significant uncertainty about whether this trend will continue, due to increased energy efficiency and outsourcing certain production offshore, whether it will reach a plateau as these trends yield diminishing marginal returns, or whether it will reverse with increasing electrification and digitalization. Therefore, the decision was made to use the recent historical data as is without adjustments to correct for this trend, as it represents a realistic and therefore plausible demand profile.

The likely future demand scenario is chosen to account for potential electrification of both heating and transportation. Recent historical demand profiles are used, with additional demand from both heat pumps and charging electric vehicles (EV). The degree of electrification is based on the most ambitious 'Leading the Way' scenario in the FES [2].

For electric heating, heat pump penetration is set at 80%. This is based on the FES, where the most ambitious scenario has over 80% of households with heat pumps, although this includes hybrids. This amounts to 324 TWh/year of heat demand; electrifying this would add approximately 130 TWh/year of electricity demand,

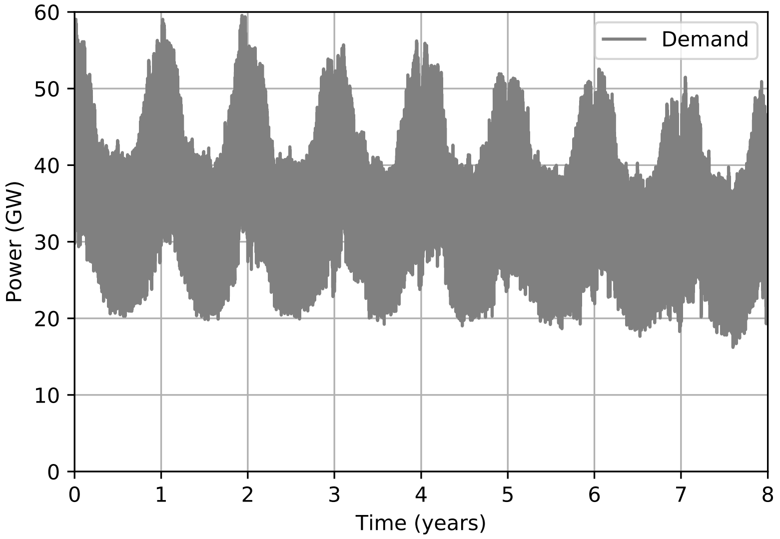


Figure 4.10: Historical GB electricity demand profile from 2009 to 2016.

although this depends significantly on the assumed coefficient of performance of the heat pumps. However, this would not be evenly distributed, because heating demand has an even stronger seasonal correlation, with most of this demand in winter, as shown in Figure 4.11.

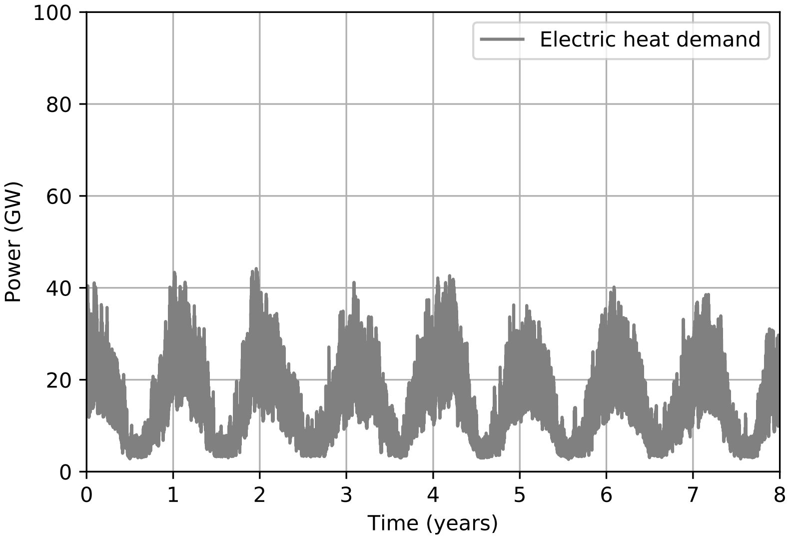


Figure 4.11: Electric heat demand profile based on historical temperature.

EV penetration is also set at 80% of current vehicle levels. The most ambitious FES scenario assumes 25 million vehicles on the road in the UK in 2050 [2], in comparison with nearly 32 million in 2020 [123]. Charging demand is based on the journeys taken rather than the number of vehicles, but these values can still be a useful benchmark for choosing a plausible future scenario. The values for the year 2050 were chosen as they are sufficiently far into the future that they represent a plausible EV demand in a future with significant renewables; however, this analysis does not aim to estimate results for a particular future year. This would add approximately 43.2 TWh/year of electricity demand. There are mild weekly and seasonal effects to charging demand based on current vehicle driving patterns, but daily effects are stronger. This may be partially due to the charging assumptions in the profiles from Crozier et al. [107], but is mostly due to the vehicle usage and travel patterns.

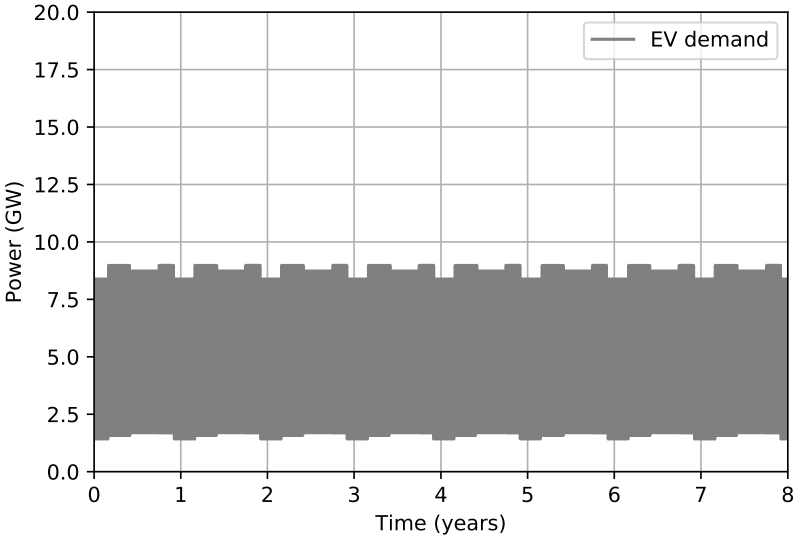


Figure 4.12: EV charging demand profile.

For this base case, both heating and EV charging as assumed to be inflexible. This yields insight into the most extreme scenario in which additional flexibility would be required. This scenario enables insight into the system requirements to provide sufficient energy and power when ideally demanded. Some of that flexibility could come from making EV charging or electric heating flexible; subsequent chapters explore the effect that this would have on remaining system requirements.

However, the scenario with inflexible assets gives a full picture of the requirements for energy shifting through time.

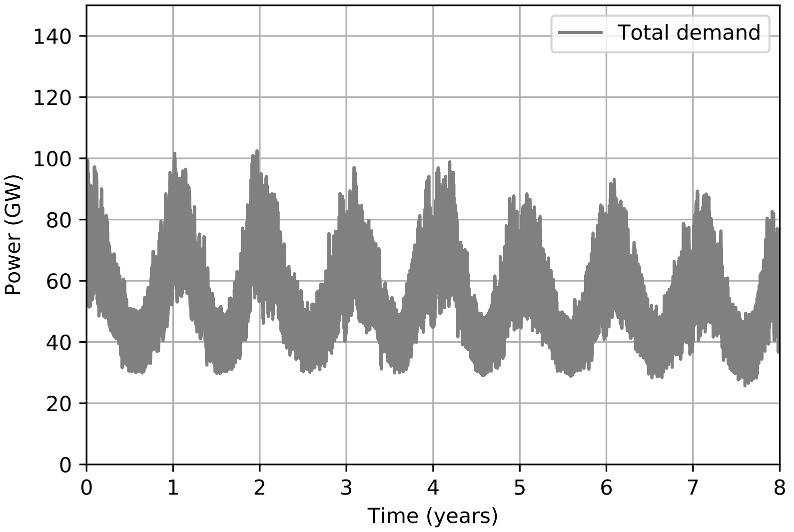


Figure 4.13: Demand for base case, including demand from inflexible electric heating and EV charging.

Annual energy demand in this base scenario with electrification of both vehicles and heating is approximately 480 TWh/year, which is about 50% larger than existing annual electricity demand. Peak demand in this scenario is still on a cold, dark winter evening, but is approximately double current peak power demand, mostly due to the addition of electric heating. The seasonal effects and annual winter peaks are clearly visible in Figure 4.13, which shows the demand profile used in the base case, including baseline demand, heating demand, and EV charging demand. The penetration of electric heating, penetration of EVs, and degree of flexibility for each are investigated further in Chapter 6.

4.2.2 Generation

The installed generation capacity is sized to generate exactly enough energy to meet all electricity demand; no excess energy is generated. This is an extreme scenario, but it enables understanding the full extent of flexibility required. Additional generation capacity, even in the form of inflexible renewables, would add flexibility into the system in the form of deciding when to curtail and when to store energy or shift demand through time to align with generation. Therefore, the base case does not include overcapacity and the effects of that additional flexibility from overcapacity and curtailment are explored further in Chapter 5.

A fully wind and solar generation mix is chosen to to understand in depth what might be needed under the most extreme scenario. There are no flexible or dispatchable generation sources in the base case. Meeting Great Britain's climate ambitions will require significant amounts of wind and solar generation to be added, which will in turn require additional flexibility. Therefore, studying a fully wind and solar system is appropriate and can provide valuable insight into flexibility requirements. Other generation mixes, including using inflexible nuclear power and some flexible dispatchable generation are investigated in Chapter 5.

The generation mix for the base case is set at 25% solar and 75% wind. This mix is chosen based on storage-size-minimizing and cost-minimizing solar wind ratio from a one year simulation of a fully renewable Great Britain [89]. That analysis used historical demand and did not include electrification of heating or transportation; in a future with significant changes to demand, the ideal solar to wind ratio may change and this is investigated further in Chapter 5. This ratio represents the energy generated by each source, not a ratio of the installed power capacity. Therefore, the base case has 116.6 GW of solar and 129.7 GW of wind installed.

The wind and solar generation profiles are shown in Figures 4.14 and 4.15 respectively. Both exhibit some seasonal patterns, although these are complementary, with solar peaks in summer and more wind in winter. There are almost no periods with no wind whatsoever, although there are many spells with very little wind generation, for example if the wind speed is below the cut in speed of the turbines. When these low-wind periods occur at nighttime or even coincide with a very cloudy winter day with little sunshine, then nearly all power demand would need to be met by flexible resources.

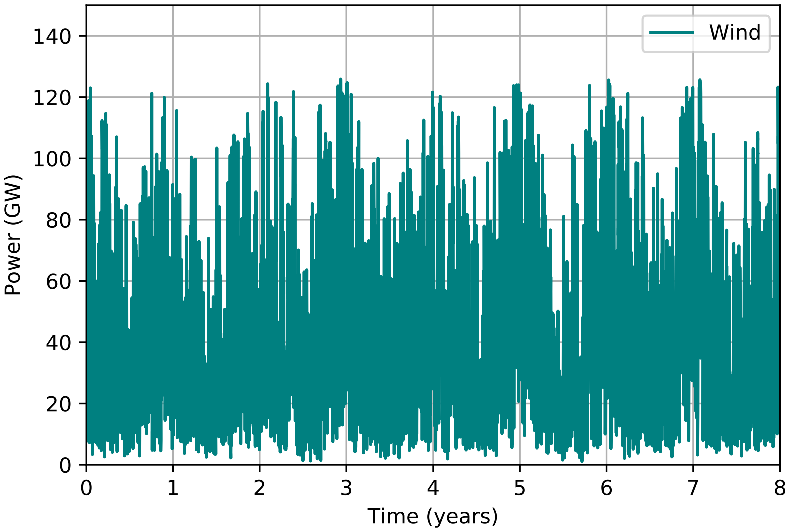


Figure 4.14: Generation profiles for wind power in the base case.

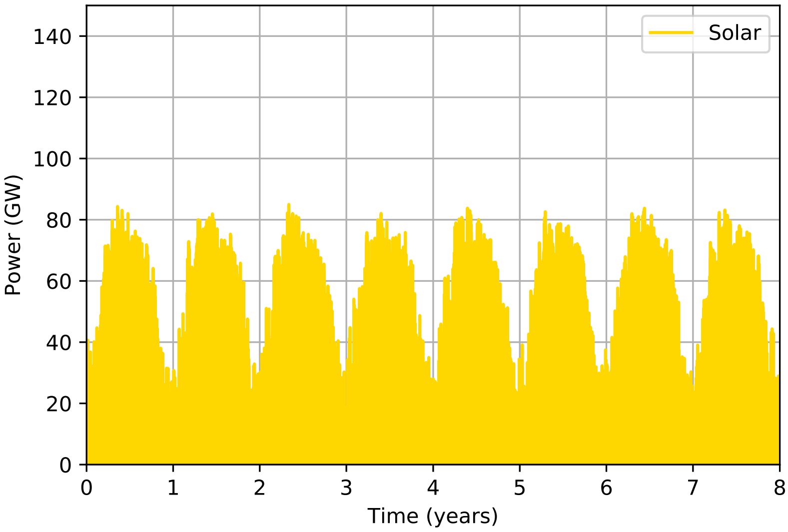


Figure 4.15: Generation profiles for solar power in the base case.

4.3 Overall flexibility requirements

4.3.1 Net Load

This section describes the overall need for energy shifting in this base scenario and the minimum capacity of the aggregated flexibility resources required to achieve this and meet demand.

Figure 4.16 shows the net load profile over eight years and Figure 4.17 shows the associated load duration curve. Values above zero indicate unmet demand, while values below zero indicate excess generation.

There is a very clear seasonal pattern in Figure 4.16, with more generation than demand in summer and more shortfall of supply in winter, suggesting at least some need for interseasonal energy shifting. Other patterns are harder to see immediately in Figure 4.16, but there is clearly also a need for shifting energy over shorter timescales.

Figure 4.17 shows a relatively even distribution of power needs, with most shortfall less and supply excess less than 50 GW. This is still a lot of power which would need to be supplied by flexible resources in this fully wind and solar world, but is on part with peak demand today. However, there are a few hours which require much more power to meet demand and also a few hours where significantly more generation must be absorbed.

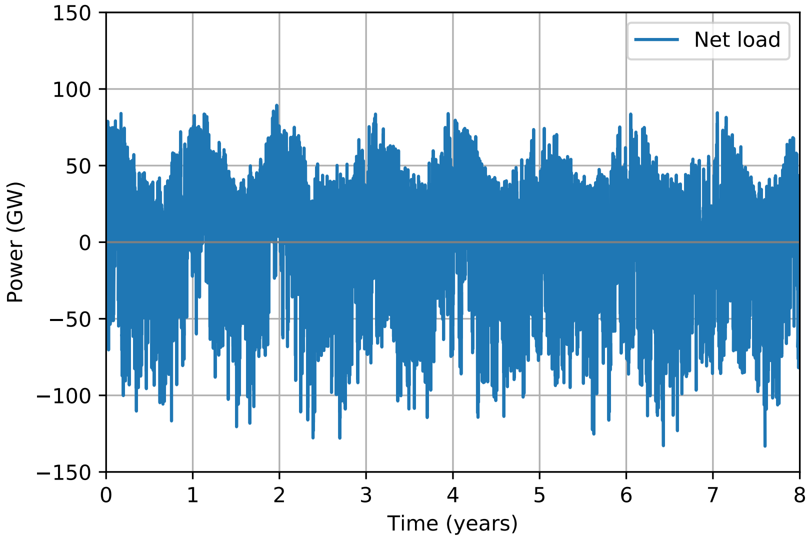


Figure 4.16: Net load for base case.

Aggregate resource capacity

This section estimates the capacity requirements of overall energy shifting resources. It does so by conceptualizing aggregate flexibility resources as a single large storage

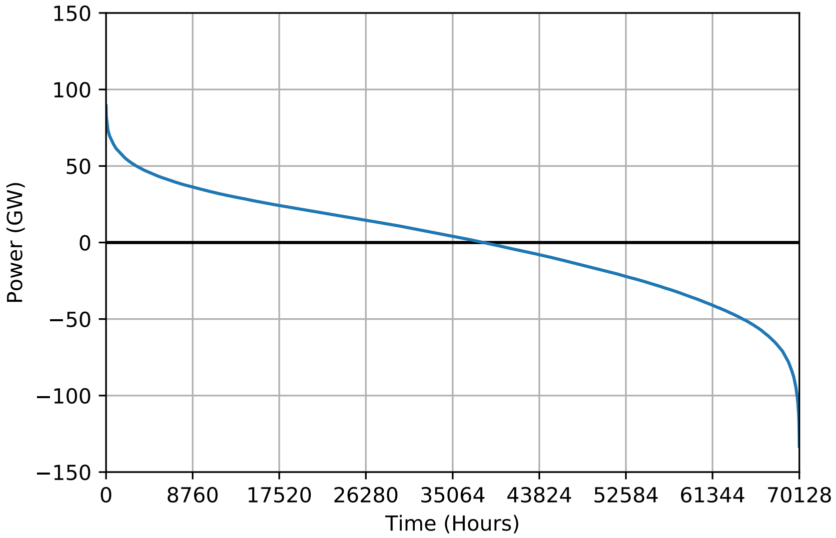


Figure 4.17: Load duration curve for net load for base case.

asset and then sizing that asset. The hypothetical overall storage asset fulfils many roles, which would in practice be completed by several different resources. In Section 4.4, these minimum overall requirements are disaggregated into different timescales, to aid in identifying portfolios of resources which could meet demand under these conditions.

The power profile of the aggregated flexibility resources will be the same as the net load profile in this scenario, as shown in Figure 4.18. The total discharge capacity required of the flexibility resources is 89.4 GW, which is the maximum value of the net load. If there were excess generation which were curtailed, then the flexibility resource profile would follow the net load for all times of supply shortfall (net load > 0), but only some of the excess generation would be utilized.

The energy profile of the flexibility resources required is shown in Figure 4.19. If these are all storage resources, then the profile shows the minimum amount of energy in storage at any given time and the minimum required capacity would be 154.6 TWh. If these are all demand shifting assets, then the profile represents the total amount of displaced energy at any given time. For context, the UK's installed non-gas energy storage is growing rapidly, but estimated to be on the order of tens of GWh [2].

There are clear seasonal patterns visible in Figures 4.18 and 4.19. However, there is also clearly a need for some shifting of energy over longer than annual timescales. From this profile, it is clear that storing energy for more than one year and carrying it over more than one annual cycle contributes to a larger overall storage size required.

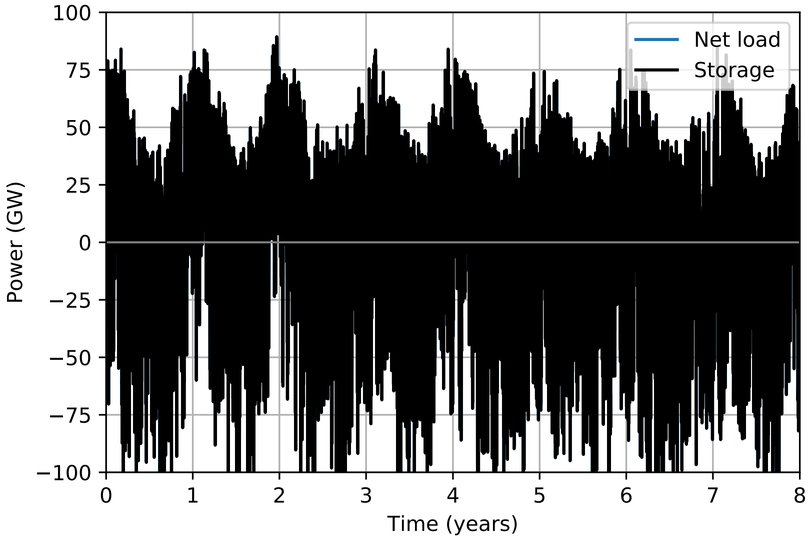


Figure 4.18: Power profile of aggregate flexibility resources required to meet demand in base case is the same as the net load when there is no excess generation.

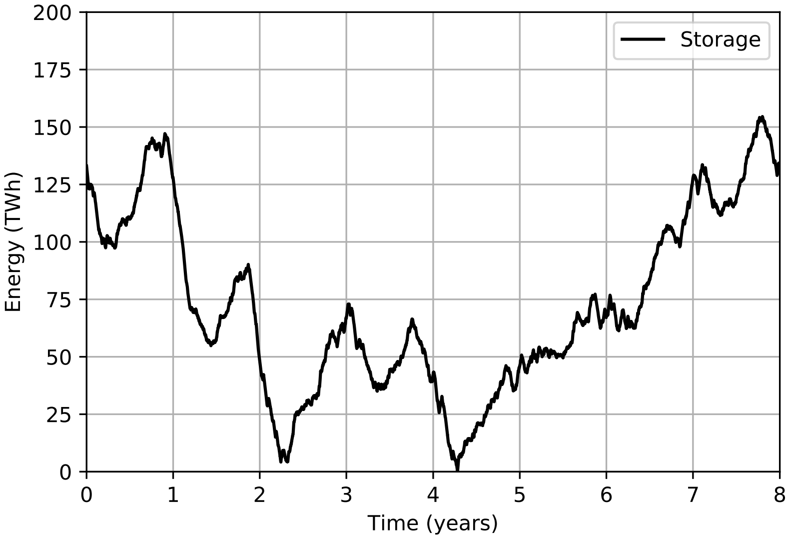


Figure 4.19: Profile of minimum amount of energy stored (or total displaced) at any time by aggregate flexibility resources required for base case.

4.4 Flexibility requirements over different timescales

This section examines the flexibility requirements over different timescales for the base scenario with fully wind and solar generation and 80% penetration of EVs and electric heating. To do this, the overall flexibility requirements identified in Section 4.3 are disaggregate based on the amount of time energy is shifted for, using the three methods in Chapter 3. First, distributions of energy shifting timescales required are identified for the FIFO and LIFO strategies. Patterns in the demand and net load profiles are identified for the filter method. Then, for all three methods, capacity requirements are estimated for resources which could shift energy over daily, weekly, annual, and longer timeframes.

The three disaggregation strategies described in Chapter 3 are used to disaggregate the overall energy shifting requirements. Each method is used to create a potential portfolio of flexibility resources which could meet demand under the conditions outlined for the base scenario.

The following sections investigate the distribution of timescales required for energy shifting using the three methods. Each method is used to disaggregate the overall energy shifting profile into profiles for shifting over daily, weekly, annual and longer timescales. The energy shifting needs over these timescales would likely be met by a portfolio of different technologies. The disaggregated energy shifting profiles are used to estimate capacities required for resources to shift energy over each timescale.

Once the distribution of requirements over different timescales has been understood, one can estimate the capacity requirements for resources which could meet different parts of this distribution by shifting energy over different timescales. This section examines the power and energy requirements for resources which could shift energy by up to one day, one to seven days, seven days to a year, and over one year. As expected, the three methods yield different values for capacity requirements, but one can draw insights into both flexibility requirements and into portfolios which could meet those requirements, from the similarities and differences in results across the methods.

4.4.1 FIFO method

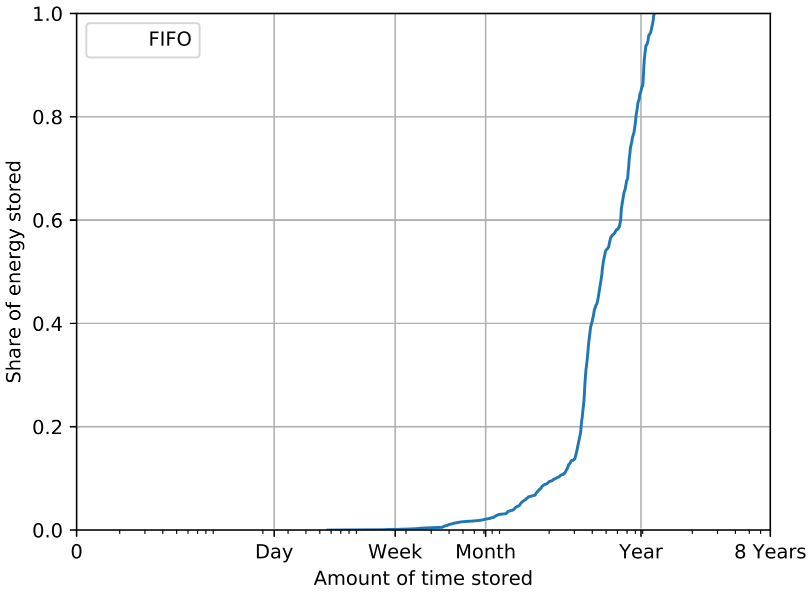


Figure 4.20: Share of all energy shifted which is shifted by up to a particular amount of time.

The FIFO disaggregation strategy can be used to identify how long each unit of energy must be shifted for, creating a distribution of energy shifting timescales shown in Figure 4.20. The horizontal axis shows the amount of time energy is shifted for and the vertical axis shows the share of all shifted energy which is shifted for that amount of time or less.

Using a FIFO disaggregation strategy, the majority of energy shifted through time is shifted interseasonally for three to six months. Very little energy is shifted for less than a week, but 80% is shifted by less than one year and all of it is shifted by less than two years. Although these results show that almost no energy is shifted by less than a few days, there will likely still be a need and role for short term energy shifting. Due to the hourly time resolution of the data, the analysis here does not estimate requirements for flexibility on shorter than hourly timescales, but less than hourly flexibility would certainly be required for system balancing in a fully renewable GB.

The FIFO strategy shows it might be possible to meet our need for temporal flexibility primarily through interseasonal energy shifting assets, for example hydrogen or ammonia storage or through additional generation with renewable curtailment. This energy shifting is extremely unlikely to be achieved through shifting demand by months, but if meeting demand with only domestic renewable generation is not possible, these flexibility requirements could be met at least in part through other means. Alternatively, those flexibility requirements may not be met by shifting energy through time but rather by shifting energy through space, for example with interconnection or using power-to-gas in another location with more renewables and shipping the gas to the UK.

Using the FIFO strategy to disaggregate the overall energy shifting profile enables the creation of new energy shifting profiles for each timescale bucket of interest. The profiles for daily, weekly, annual, and longer than annual energy shifting needs are shown in Figure 4.21.

From these profiles, capacity requirements for these resources can be estimated in the same way as for the overall energy shifting profiles. Table 4.1 shows the energy and power requirements for each of these timescales. This is the aggregate capacity required for resources which can shift energy for those durations and each of these will comprise many different assets. Therefore, it does not necessarily make sense to make claims about the energy to power ratios of the resources required, except to note that these are measured in different orders of magnitude. Although the power capacity requirements for the longer term resources are very high, nearly peak power demand, most of the time they are required to discharge at amounts well below the maximum.

Table 4.1: Capacity requirements for resources which can shift energy over different timescales found using the FIFO strategy.

FIFO	**< 1 day**	**1-7 days**	**7-365 days**	**< 365 days**
Energy capacity (TWh)	0	0.74	116.2	115.5
Power capacity (GW)	0	54.8	89.4	82.6

4.4.2 LIFO method

The LIFO disaggregation strategy could be used to create a different but equally plausible portfolio of resources to address flexibility requirements and meet demand. In this case, the majority of energy is shifted by less than one month, with nearly half of this shifted by less than one day. However, about 10% of all shifted energy would need to be shifted by more than two years. Although the need to shift energy by up to half a year is relatively evenly distributed, the energy shifting over longer timescales clearly follows a seasonal or annual pattern, with steps visible at the multi-annual durations at the right in Figure 4.22.

The results from the LIFO strategy shows that it is possible to meet significant energy shifting needs with technologies which exist today, including batteries, pumped hydropower storage, and demand shifting. The multi-year energy shifting could potentially be met by hydrogen or ammonia storage or through additional generation paired with curtailment of excess renewables.

Figure 4.23 shows the profiles of the daily, weekly, annual, and longer energy shifting resources found using the LIFO strategy. The aggregate capacity requirements for these four resources are shown in Table 4.2.

In this resource portfolio, the resources which shift energy for up to one day and up to one week are much smaller than the longer term resources, although they are still quite large on the order of terawatt-hours. However, in contrast with the FIFO case, these short-term resources are much more heavily utilized, which can be see from the profiles in Figure 4.23. Although the power capacity requirements for each type of resource are very high, over 100 GW, most of the time they are required to discharge at amounts well below the maximum. This suggests that there are a few moments when this algorithm has assigned nearly all unmet demand to be met by one type of resource and those moments determine the capacity requirements.

4.4.3 Filter method

Another way to think about the energy shifting timescales which might be required is to investigate existing patterns in demand and supply, enabling choosing resources

Table 4.2: Capacity requirements for resources which can shift energy over different timescales found using the LIFO strategy.

LIFO	**< 1 day**	**1-7 days**	**7-365 days**	**< 365 days**
Energy capacity (TWh)	0.52	2.86	48.4	111.5
Power capacity (GW)	73.9	83.7	89.4	84.0

which align effectively with these patterns. Figure 4.24 shows Fourier transforms of the demand profile and net load profile for this base scenario.

Unsurprisingly, daily and annual patterns are strongest in both demand and the net load. This suggests that resources which could effectively shift energy over these timescales might be most useful. For example, for the daily energy shifting requirements, this could take the form of storage assets, with charge and discharge cycles which operate efficiently over daily timescales. Alternatively, demand shifting of certain activities by a day or half a day may be as easy or even easier than by a few hours, for example shifting some demand to the morning from the evening or doing something a day later than initially planned.

The demand profile has a clear weekly pattern, but this is not apparent in the net load profile. Unlike the daily and annual patterns to demand which are related to natural phenomena, weekly rhythms in the demand profile are entirely from the social practice of dividing time into weeks and are absent from the generation profiles. Although one might expect a weaker weekly signal in the net load than in demand, it is outweighed by the generation patterns and not visible in the net load.

Figure 4.25 shows the profiles of the daily, weekly, annual, and longer energy shifting resources found using the filter strategy. The aggregate capacity requirements for these four resources are shown in Table 4.3.

As with the LIFO strategy, the resources to shift energy up to one day and up to one week are quite heavily utilized and have many more charge and discharge cycles than the longer-term resources.

The power capacity requirements for each resource type are much lower than for FIFO and LIFO and than the overall power capacity requirement, which suggests multiple resources type are always operating simultaneously to meet demand.

Table 4.3: Capacity requirements for resources which can shift energy over different timescales found using the filter strategy.

Filter	**$<$ 1 day**	**1-7 days**	**7-365 days**	**$<$ 365 days**
Energy capacity (TWh)	0.25	2.0	35.7	122.1
Power capacity (GW)	45.7	74.1	60.0	17.3

4.5 Key takeaways

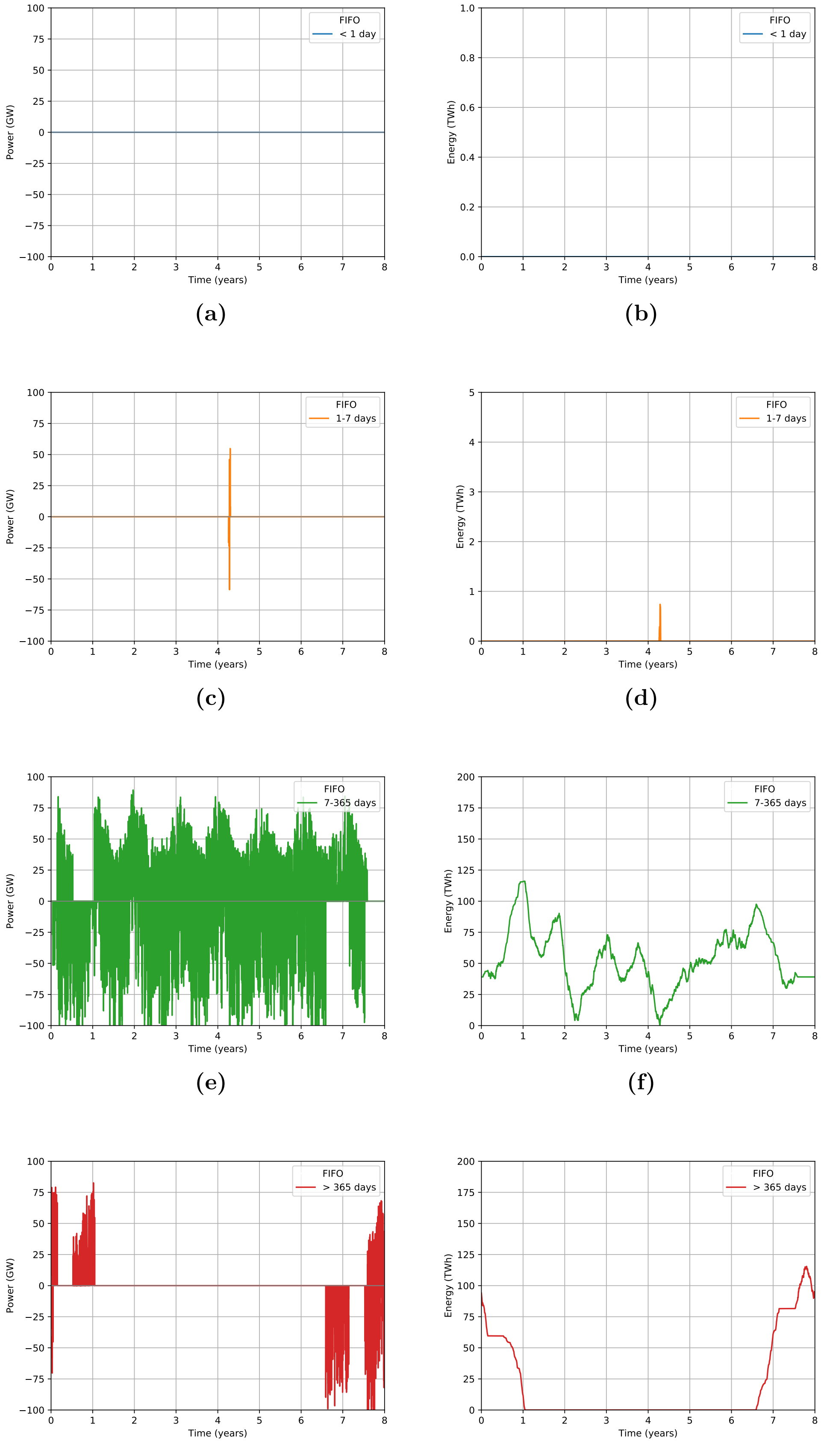
A highly renewable and electrified Great Britain will require significant amounts of flexibility to successfully meet demand and ensure a stable power system. This flexibility to shift energy will be needed over several timescales, from hours to potentially years.

An ambitious future scenario is created as a base case. On the supply side, solar and wind power provide enough energy to meet all demand. For the base case, the solar to wind ratio is set at 1:3, with 25% of energy generated from solar and 75% from wind, based on the cost-minimizing generation mix in a one year simulation of Great Britain [89]. In addition to current electricity demand, the future demand profiles include electrifying 80% of domestic heating and 80% of private vehicles, based on the National Grid Future Energy Scenarios.

Multiple different flexible resource portfolios could potentially meet demand in a fully renewable and highly electrified future system. Distinct portfolio options with different capacities for daily, weekly, annual, and longer than annual resources are created using the three methods in Chapter 3. In all three cases, the energy capacity requirements for daily and weekly storage were orders of magnitude smaller than the sizes required for interseasonal or interannual energy shifting. However, depending on the strategy chosen, these daily and weekly resources could account for a significant portion of all energy shifting required, if they are frequently utilized.

In this ambitious future scenario, with 80% of all vehicles and domestic heating electrified and exactly enough solar and wind generation installed to meet demand, Great Britain would require over 150 TWh of flexibility resources which could discharge at nearly 90 GW, more the 50% greater than current peak power demand.

This is clearly an extreme scenario and unlikely to be realized, but it is still helpful to understand these limits and how they depend on different system configurations. Subsequent chapters investigate how these results vary under different scenarios and how they depend on assumptions about generation, demand, and the system.



(a) **(b)**

(c) **(d)**

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(g) **(h)**

Figure 4.21: Profiles of resources which could shift energy for daily, weekly, annual, and longer timescales in potential portfolio created using FIFO strategy.

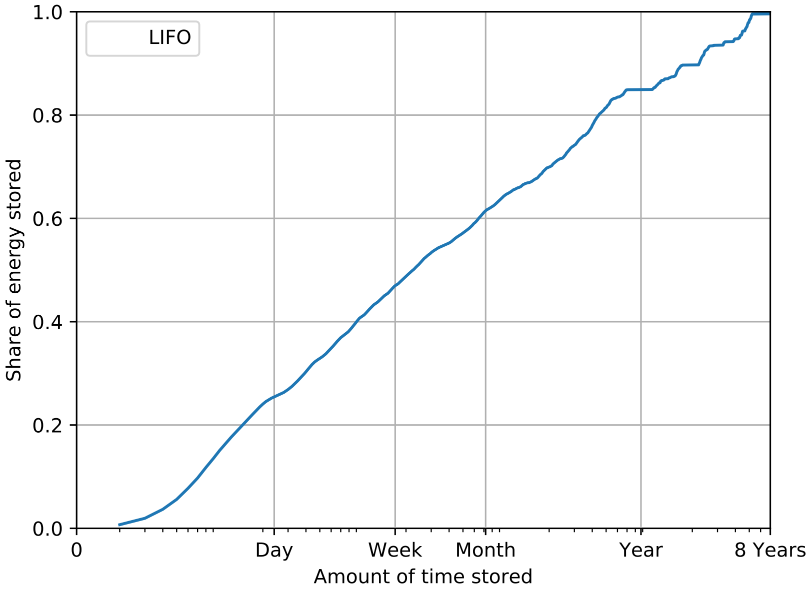
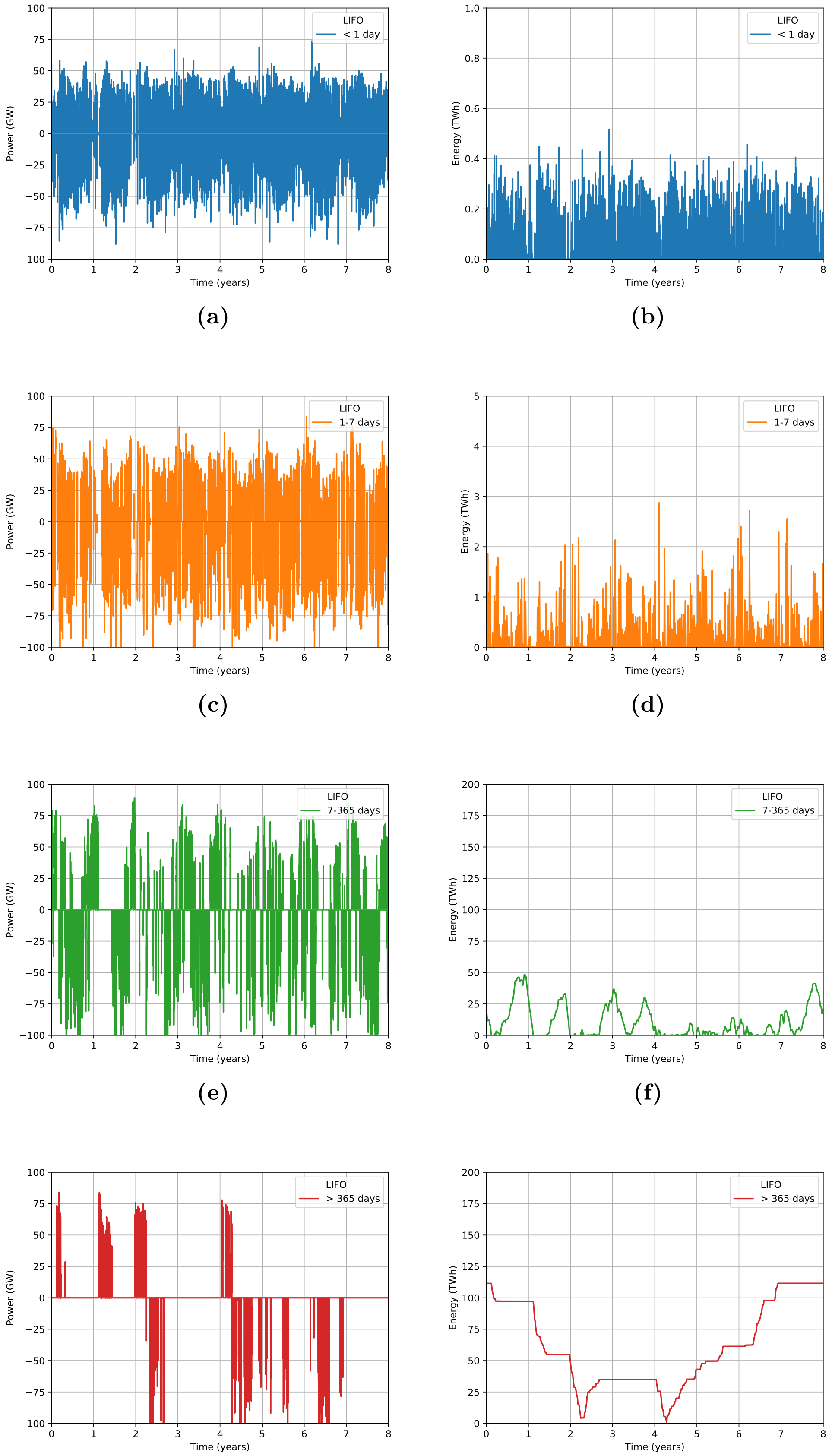


Figure 4.22: Share of all energy shifted which is shifted by up to a particular amount of time.



(a) **(b)**

(c) **(d)**

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(g) **(h)**

Figure 4.23: Profiles of resources which could shift energy for daily, weekly, annual, and longer timescales in potential portfolio created using LIFO strategy.

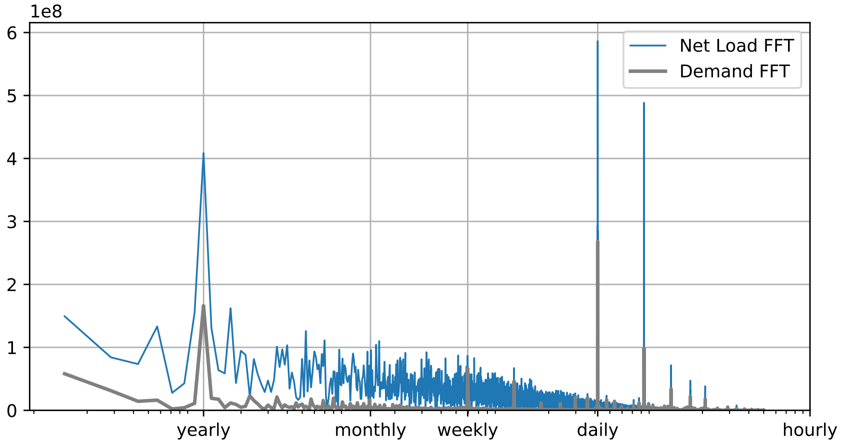
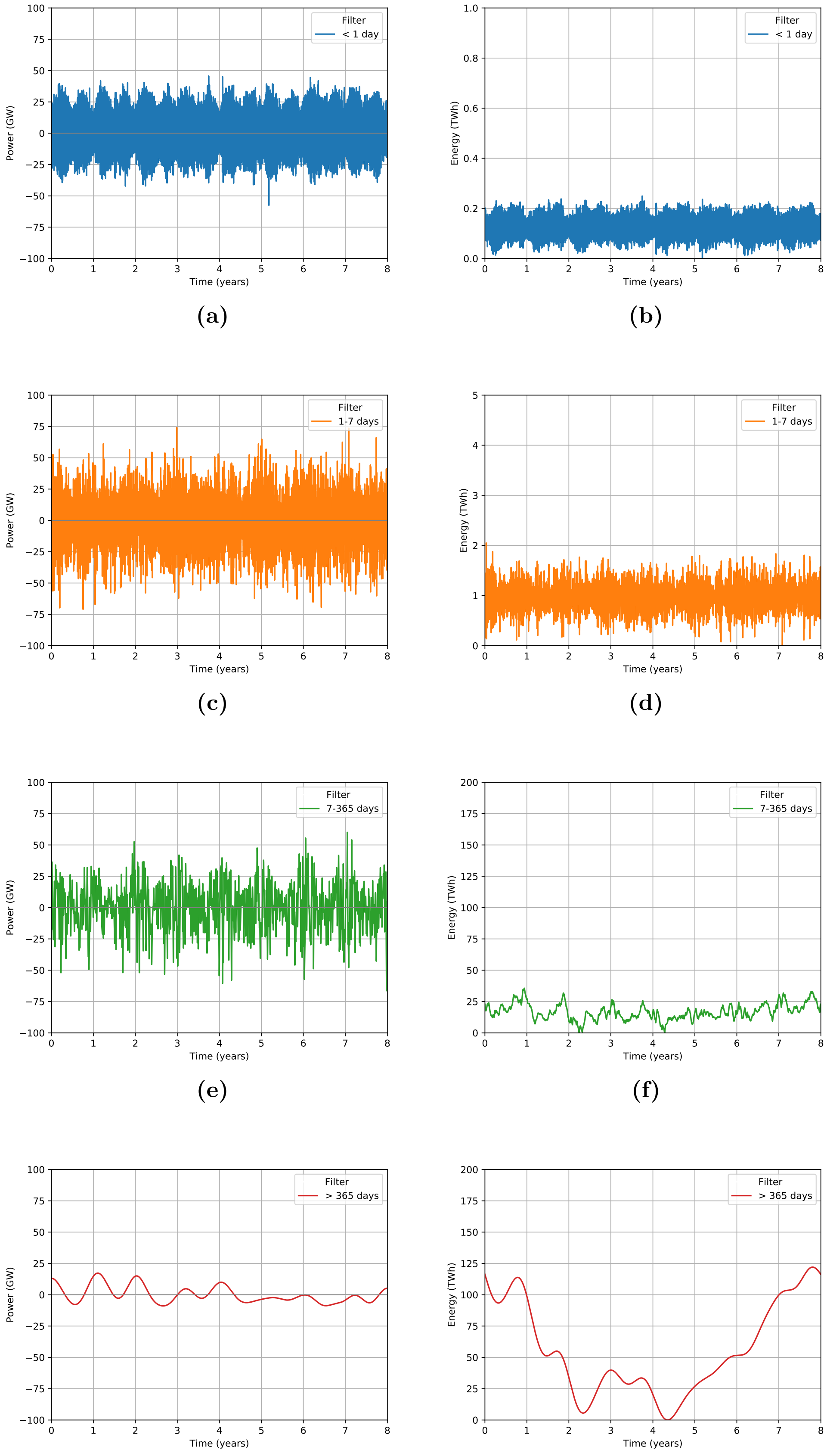


Figure 4.24: Fourier transform of demand profile and net load profiles.



(a) **(b)**

(c) **(d)**

(e) **(f)**

(g) **(h)**

Figure 4.25: Profiles of resources which could shift energy for daily, weekly, annual, and longer timescales in potential portfolio created using the filter strategy.

5

How temporal flexibility requirements depend on generation

This chapter investigates how temporal flexibility requirements in highly renewable power systems depend on the generation mix, using the case of Great Britain. This problem can be broken up into several research questions, including how the share of variable renewable generation affects the need for energy shifting, how overcapacity of renewable generation affects the need for energy shifting, how the solar to wind ratio in the generation mix affects the need for energy shifting, and how the efficiency of energy shifting available affects system requirements. To enable investigating these effects of varying supply and system parameters, demand is consistent across all scenarios in this chapter; how changes to demand could affect flexibility requirements is covered in Chapter 6.

Given the uncertainty about future energy system configurations, it is important to investigate how system flexibility requirements depend on the generation mix [32], rather than assess the optimal strategy for a particular set of conditions or very specific detailed estimates for a handful of potential future scenarios. Generation and network infrastructure projects have long lead times, with decisions about policy and investment often made years in advance of power plant construction and connection. There are tradeoffs between different infrastructure options, but also some low-regret options which preserve future optionality. Therefore, it is useful to study a range of potential future scenarios and understand how flexibility requirements depend on each of those parameters.

To address the overarching question, it is broken down into the follow sub-questions.

1. How do flexibility requirements depend on the share of variable renewable energy (VRE) in the generation mix?
2. How does overcapacity of renewables affect remaining flexibility requirements?
3. How does the ratio of solar to wind in the generation mix affect the flexibility requirements, for fully wind and solar powered systems?

With the share of solar and wind power both increasing faster than anticipated over the past decade, the question of how the share of wind and solar generation will affect the need for flexibility is extremely relevant.

Within the increasing share of renewables, understanding the impact of the generation mix can yield insight into the types of resources which may be needed to balance future power systems. For example, if one knew that shifting energy within a day would be required at least to some degree regardless of the solar to wind ratio, then decisions about policy, regulation, and investment could work toward ensuring the system had adequate flexibility resources which could shift energy over that timescale. Alternatively, if some generation mixes or system configurations required flexibility over timescales where technology to do that energy shifting does not currently exist affordably at scale, then one could make decisions to avoid that future scenario or to invest in research and development of appropriate flexibility resources.

To address the other questions beyond the effects of VRE share, the other sections use scenarios where all electricity is supplied by wind and solar photovoltaic (PV) generation for the case of Great Britain (GB). The analysis of these extreme scenarios is useful for insights into system potential and limits, but not an expectation or recommendation for future power systems.

The results presented here are applicable only to Great Britain, although some insight may be gleaned for locations with similar weather patterns and demand patterns. These results depend on the temporal alignment between demand renewable supply, so similar weather patterns alone or similar demand alone would not immediately suggest these results would be applicable.

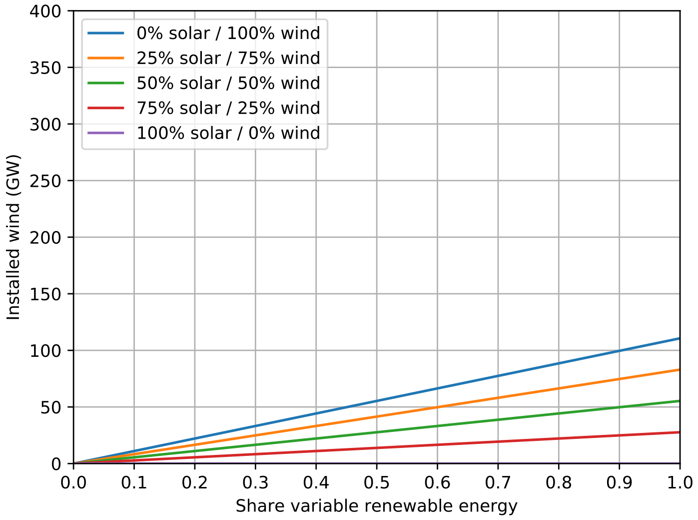
The remainder of the chapter addresses each of the research questions using the case of Great Britain. Section 5.1 investigates how flexibility requirements depend on the share of variable renewables in the system. Section 5.3 investigates the effects of additional renewable generation capacity on remaining flexibility requirements and estimates the value of additional marginal generation capacity in terms of flexible resource needs avoided. Section 5.2 builds on this analysis and dives into the effects of the solar wind ratio in the generation mix, for systems with fully variable renewable generation.

5.1 Effect of variable renewable energy penetration on temporal flexibility requirements

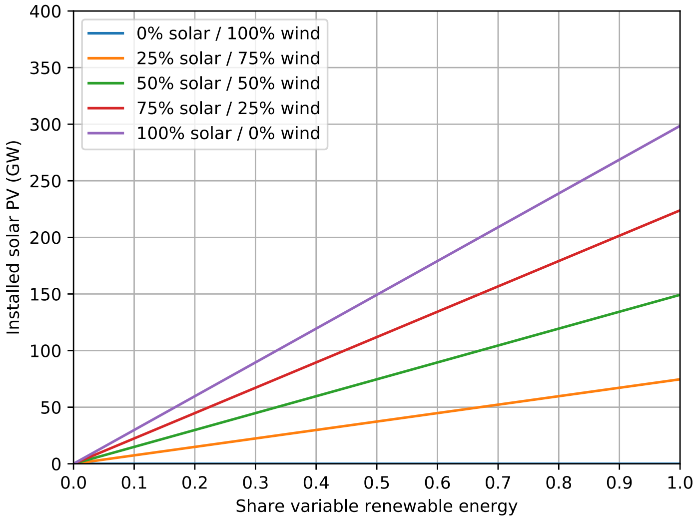
This section addresses the question of how temporal flexibility requirements depend on the share of variable renewable energy (VRE) in the generation mix. Variable renewables considered here include solar and wind power only. Remaining electricity demand is met either by additional flexible dispatchable generation (e.g. gas, hydropower, imports) or by inflexible generation with a flat power profile (e.g. nuclear power). Section 5.1.1 presents results if the remaining generation is flexible, while Section 5.1.2 includes results if the remaining generation is inflexible.

For all scenarios in this section, the generation capacity is sized to meet 100% of electricity demand. The installed capacities of wind and solar generation for these simulations are shown in Figure 5.1. For other locations with different weather patterns and therefore different solar and wind capacity factors, the relative slopes of these curves would be different.

The share of variable renewable energy refers to the share of electric energy demanded which is met by solar and wind generation. For example, if the share of variable renewable energy is 0.6, then solar and wind combined produce 60% of energy and 40% comes from other generation. The solar and wind generation mix percentages refer to the share of variable renewables, not to the overall generation mix. Therefore, a scenario labeled 25% solar / 75% wind for 60% VRE would overall have 15% of energy from solar, 45% from wind, and 40% from other sources.



(a) Wind



(b) Solar

Figure 5.1: Installed generation capacity for different shares of variable renewable energy.

One would expect the penetration of variable renewables to be positively correlated with the need for additional temporal flexibility. The solar and wind generation is inflexible and may not be generated when or where it is demanded. Therefore systems with more VRE will require more flexibility, including shifting energy through time, to keep them in balance.

One might expect different results depending on the other generation sources. More additional flexibility would likely be required in a completely inflexible system, where for example the non-VRE share is provided by inflexible nuclear power, than in a system where the non-VRE share is provided by dispatchable generation, such as biogas or hydropower.

5.1.1 Results: Using flexible generation

Systems with high penetrations of solar and wind generation require more temporal flexibility to shift energy over time. In these scenarios, the non-VRE generation is completely flexible and dispatchable as needed. This enables calculating the minimum possible additional flexibility requirements; constraints from the non-VRE generation technologies, such as ramping rates or minimum up time, would increase the need for system flexibility. Furthermore, one could think of this non-VRE generation as other system flexibility, and therefore the estimates here are for remaining system flexibility required. For example, this could be the temporal flexibility needed from shifting energy through time, after accounting for spatial flexibility from interconnectors or imports of hydrogen or ammonia.

Overall requirements

As expected, increasing the share of variable renewable energy in the generation mix increases the need for temporal flexibility and the size of the aggregate flexibility resources required.

Figure 5.2 shows how both the energy capacity and the power capacity of aggregate energy shifting resources increase with VRE penetration, for all solar to wind ratios in the generation mix. Although they both increase with more VRE, they exhibit very different characteristics with regard to how they are affected by a marginal unit of VRE. For each additional unit of VRE, the energy capacity required increases more than was required by the preceding unit, while the power capacity increases less than was required by the preceding unit (for VRE $>$ 20%).

Although significantly less than the tens to hundreds of terawatt-hours which may be required for fully solar and wind systems, the size of aggregated flexibility assets required for VRE shares between 20% and 50% is still significant, on the order of gigawatt-hours.

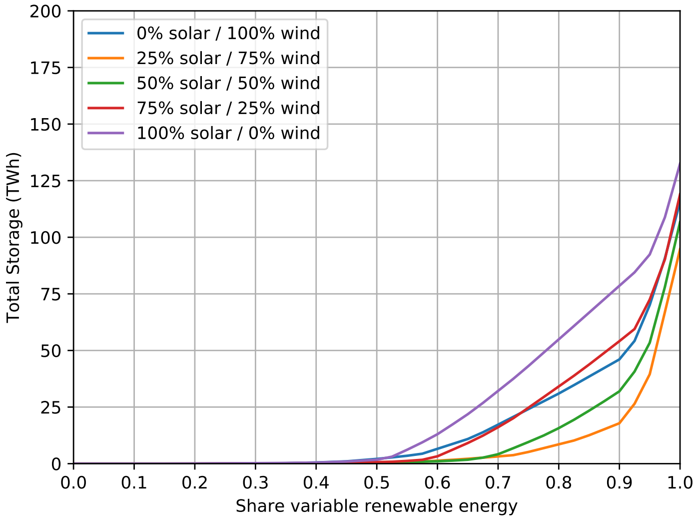
Requirements over different timescales

As expected, flexibility requirements over all timescales increase with the share of VRE in the system and systems with high shares of VRE need to shift energy for longer periods of time. Systems with at least 25% VRE need the ability to shift energy by up to a day, shown in top row panels of Figure 5.3. Figure 5.3 also shows the need to shift energy by more than one week only affects systems with more than 50% VRE and even high shares of VRE can be tolerated without longer term energy shifting under some generation mixes. Depending on the generation mix and the resource portfolio available, it may be possible to have a system with up to 95% VRE without the need to shift energy for longer than one year, as shown in bottom row of Figure 5.3.

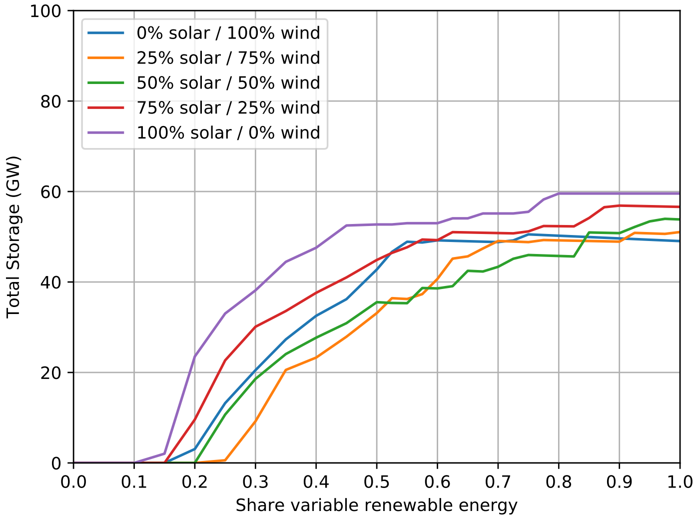
5.1.2 Results: Using flat inflexible nuclear generation

Overall requirements

One would expect that increasing the share of inflexible variable renewable energy would increase the flexibility required, even when the remaining demand is met by inflexible but flat nuclear generation. This seems obvious when the alternative is flexible dispatchable fossil fuel generation, because that flexibility would need to come from somewhere. But one would also expect increasing solar and wind to increase flexibility needs at least somewhat when the remaining demand is met by inflexible flat nuclear power. This is because there are periods of time without wind



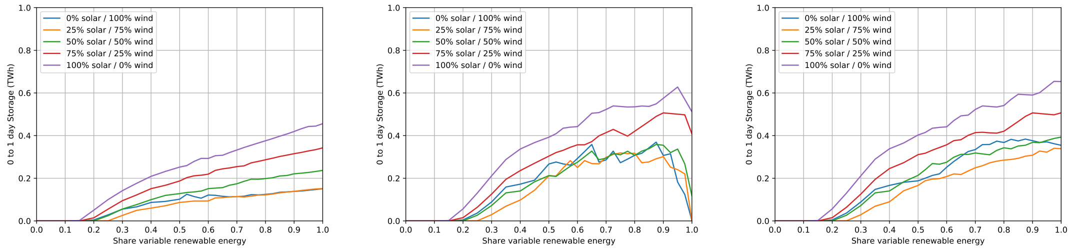
(a) Energy



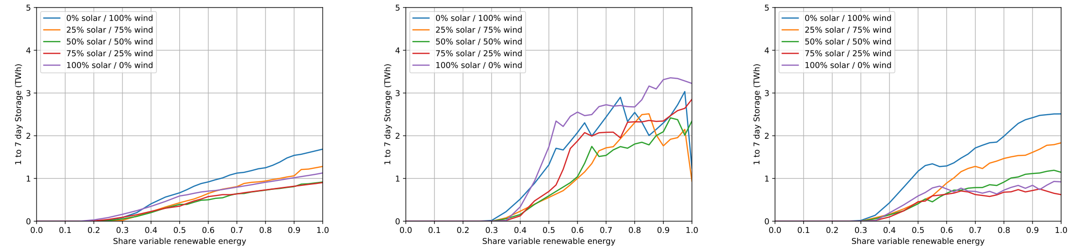
(b) Power

Figure 5.2: Overall storage capacity required for different shares of variable renewable energy, where remaining demand is supplied by additional flexible generation.

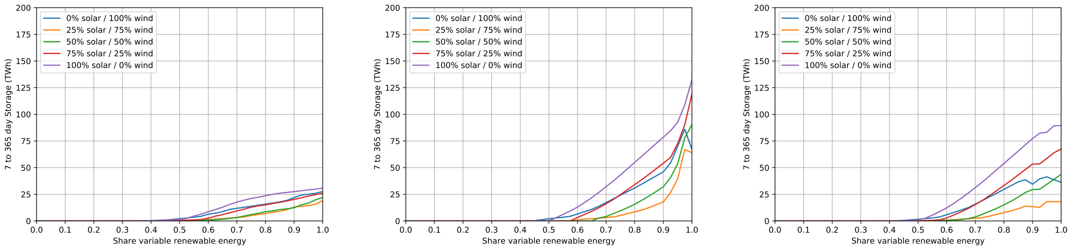
and sunshine, while the non-variable renewable power profile here is assumed to be completely flat, so there are no times without power. In reality, even nuclear power stations have downtime especially for maintenance, but this is neither long nor frequent and usually scheduled well in advance, so the flat power profile assumption is adequate for these purposes. Therefore, the difference between power demanded



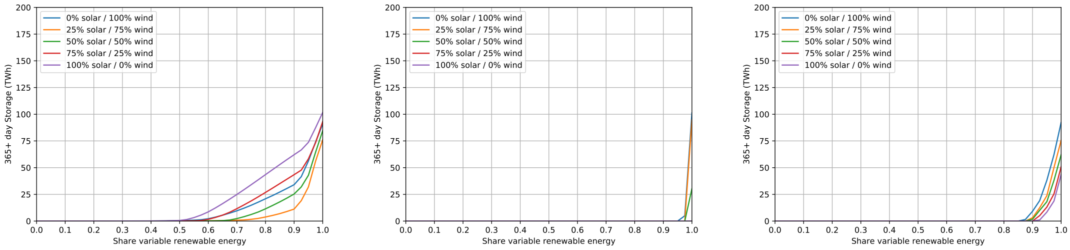
(a) Filter **(b)** FIFO **(c)** LIFO



(d) Filter **(e)** FIFO **(f)** LIFO



(g) Filter **(h)** FIFO **(i)** LIFO



(j) Filter **(k)** FIFO **(l)** LIFO

Figure 5.3: Storage capacity needed to shift energy by up to one day (top row), 1-7 days (second row), one week to one year (third row), and over one year (bottom row), estimated using three methods, for different shares of variable renewable energy

and power supplied by the flat source is smaller on average than the difference between demand and power supplied by variable renewables.

Figure 5.4 shows that increasing the share of solar and wind in the generation mix increases the need for flexibility in terms of both energy and power.

Solar dominated energy mixes require more flexibility in terms of larger storage sizes and greater discharge capacity than wind dominated mixes at all penetrations of variable renewables. For shares of variable renewables below 60%, fully wind and nuclear generation mixes require the smallest storage sizes. However, for greater shares of variable renewables, the fully wind and nuclear mix requires more storage than generation mixes which also have some solar. This is likely due to the seasonally complementary nature of solar and wind potential in Great Britain. The relationship between renewable generation mix and flexibility requirements is further investigated in Section 5.2.

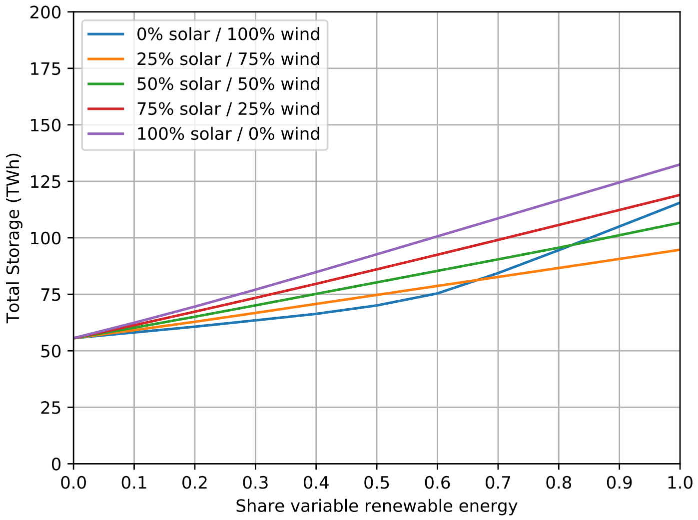
Requirements over different timescales

These overall storage requirements can be disaggregated into requirements over different timescales.

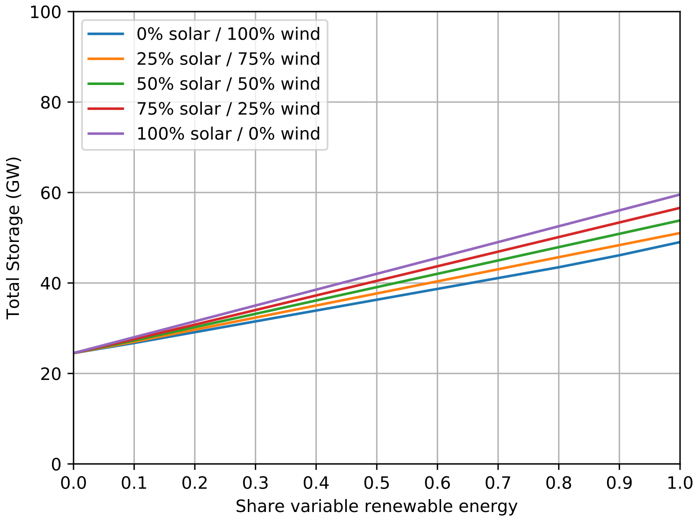
For all methods and for nearly all timescales, the capacity for flexibility resources which can shift energy over that time increases with the VRE share. The exception appears to be longer than annual energy shifting for solar heavy generation mixes, when disaggregated using the FIFO strategy. In this case, the scenarios with higher VRE shares have less flat baseload nuclear power, which generates the same power all year around every year, although demand in GB is higher in winter.

For fully wind systems, the change in slope at higher VRE shares and upward curve relative to trends for other solar wind ratios seen in Figure 5.4 is mirrored by the 100% wind curve for 7-365 day energy shifting in the LIFO panel of Figure 5.5 and the annual energy shifting in the filter panel of Figure 5.5. This suggests that the energy is likely shifted for about a year, although the specific disaggregation strategies allocate this into two different buckets.

The need to shift energy by up to a week, shown for up to a day in the top row of Figure 5.5 and for one to seven days in the second row, could be met by flexibility resources with aggregate capacity on the order of a few terawatt hours. The trend is clear that increasing VRE share increases the flexible resource sizes needed, for all



(a) Energy

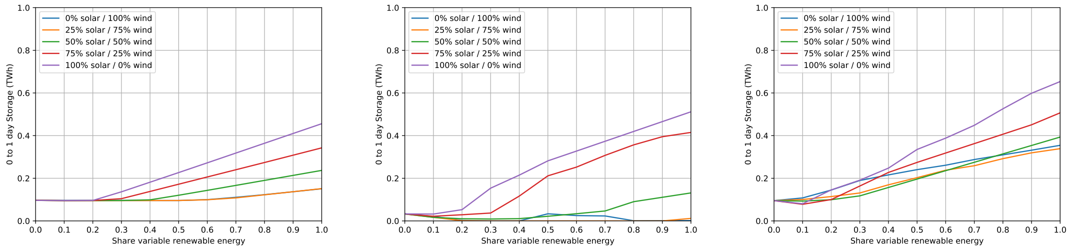


(b) Power

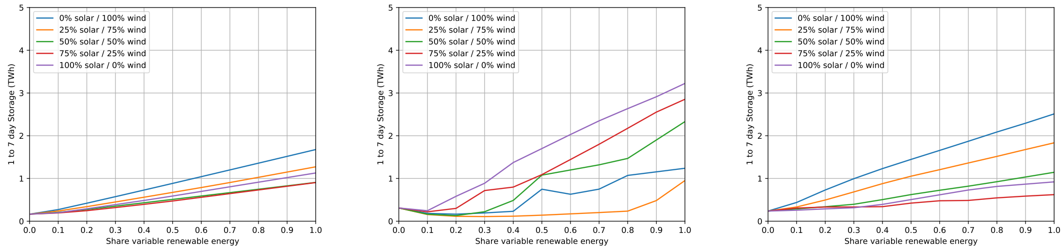
Figure 5.4: Overall storage capacity required for different shares of variable renewable energy, where remaining demand is supplied by inflexible nuclear generation.

generation mixes and for all methods. The solar dominated generation mixes clearly require greater capacity to shift energy by up to a day than the wind dominated mixes. For up to weekly timescales, there is no clear trend about the effect of the solar to wind ratio with the VRE share.

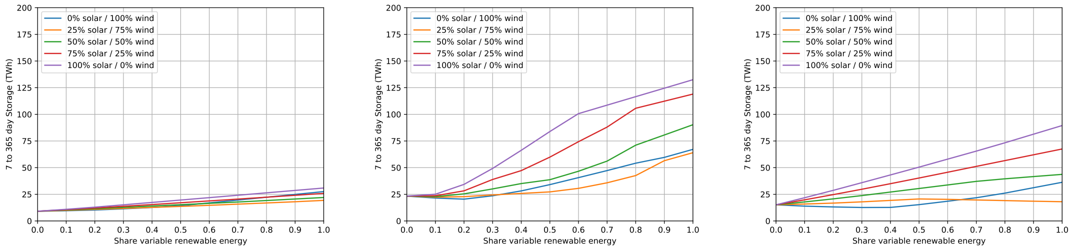
Subsequent analyses use the case with 100% variable renewable penetration to



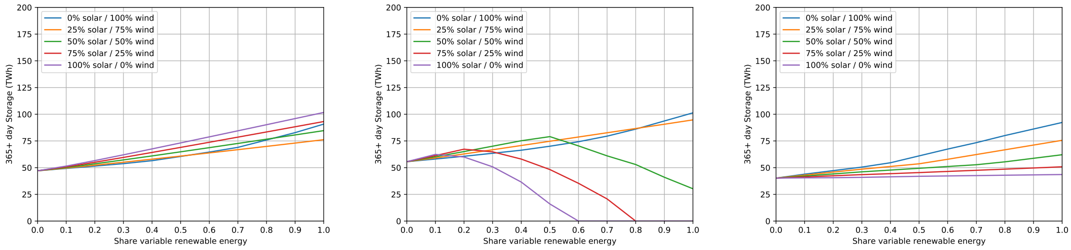
(a) Filter **(b)** FIFO **(c)** LIFO



(d) Filter **(e)** FIFO **(f)** LIFO



(g) Filter **(h)** FIFO **(i)** LIFO



(j) Filter **(k)** FIFO **(l)** LIFO

Figure 5.5: Storage capacity needed to shift energy by up to one day (top row), 1-7 days (second row), one week to one year (third row), and over one year (bottom row), estimated using three methods, for different shares of variable renewable energy

better understand system limits and draw insights from this extreme case.

5.2 Effect of solar wind ratio on temporal flexibility requirements

This section investigates the relationship between the solar to wind ratio in the generation mix and the need to shift energy over different timescales, for electricity systems with 100% variable renewable generation.

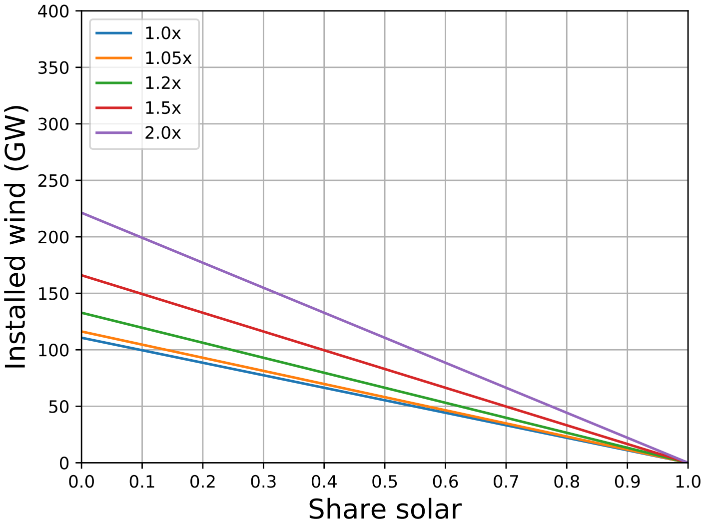
One would expect the solar to wind ratio in the generation mix to have an effect on temporal flexibility requirements. In particular, solar dominated mixes require flexibility over daily timescales in all locations, as solar power can only be generated during the day while demand for electricity continues at least to some degree at night. Given the strong seasonal sunlight patterns due to Great Britain's latitude, solar dominated mixes are expected to also require some interseasonal flexibility to account for the temporal misalignment between more generation in summer and more demand in winter.

In contrast, wind dominated energy mixes would be expected to require less seasonal energy shifting than solar dominated mixes, given that winter has both slightly more demand and slightly higher wind capacity factors. Wind patterns of course are also dependent on latitude. Finally, generation mixes with a combination of solar and wind are expected to require less energy shifting than fully wind or fully solar systems, as there are fewer times without both sun and wind than without just one and potential complementarity of solar and wind availability.

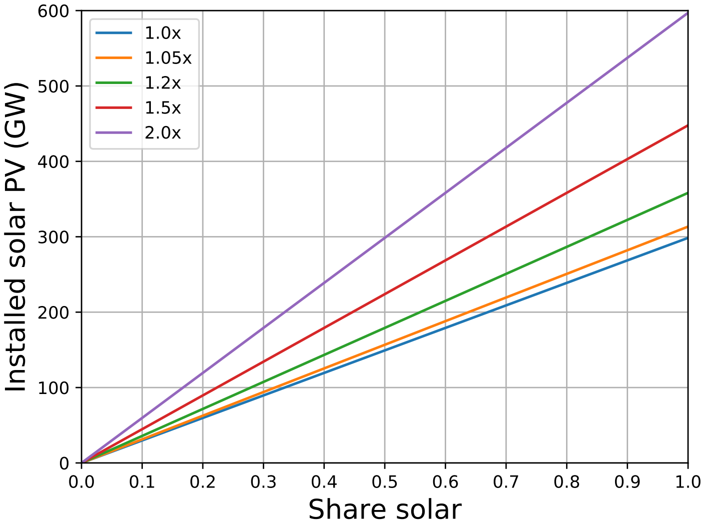
Scenarios with exactly enough generation to meet all demand and with select amounts of additional generation (5%, 20%, 50%, and 100%) are included in the generation mix analysis, although the effects of overcapacity are analyzed in Section 5.3. For some context, the installed generation capacity which would be needed for these scenarios is shown in Figure 5.6.

5.2.1 Overall requirements

The overall energy shifting requirements depend on the solar wind ratio in the generation mix, with the required sizes for aggregate energy shifting resources shown in Figure 5.7.



(a) Wind



(b) Solar

Figure 5.6: Installed generation capacity for different solar wind ratios in the generation mix for different levels of renewable generation capacity.

In terms of energy requirements, systems with a mix of wind and solar power require smaller storage capacity than fully solar or fully wind powered systems. The solar wind ratio which would minimize required storage size in a fully renewable Great Britain depends on the amount of overcapacity, but appears to be between 10% and 30% solar with the rest provided by wind. Wind dominated mixes require significantly smaller storage sizes in systems with more than 20% additional generation capacity than the solar dominated systems. This is expected, as the solar overcapacity does not increase generation at night and therefore does not address the need for diurnal flexibility.

In terms of power requirements, the effect of the solar wind ratio in the generation mix is less stark but still noticeable. The power discharging requirement for aggregate flexibility resources is the maximum of the net load. Because Great Britain's peak power occurs on winter evenings when there is little to no sunlight, the peak load is also the peak net load in solar dominated mixes. Therefore, the flexibility resources would be expected to meet that peak load in solar dominated mixes. The power requirements of wind dominated mixes are slightly less, indicating that there is probably some wind power being generated at those peak net load times, but the flexibility resources would still be expected to meet the majority of power demand at those times. Essentially, since they are intermittent sources, the flexible resources must be able to completely supply power for as long as both are unavailable.

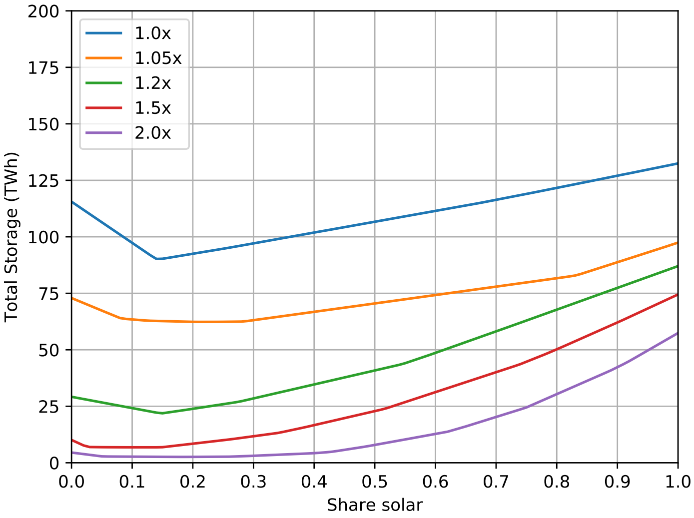
These results align with those from Cárdenas et al. [89], whose single year case study of Great Britain found that storage capacity required is minimized for generation mixes around 21% solar and 79% wind at a 1.05x overcapacity.

5.2.2 Requirements over different timescales

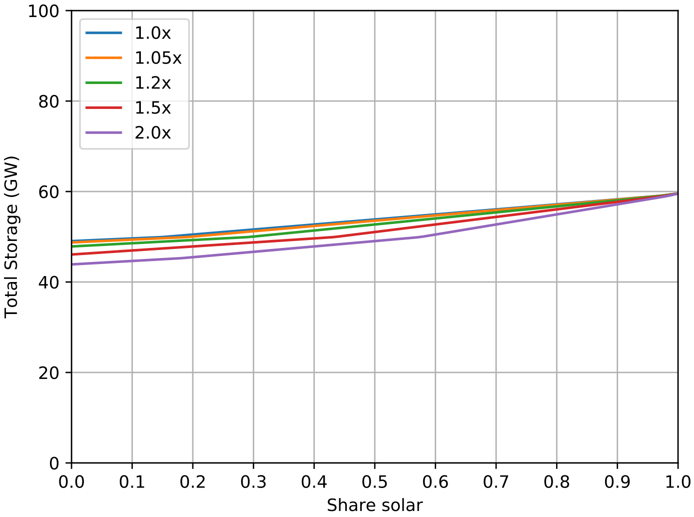
This section shows how the requirements for shifting energy over different timescales vary with the solar wind ratio in the generation mix. First, the FIFO and LIFO storage disaggregation methods are used to further investigate the distribution of timescales for which energy would need to be stored or shifted. Then, all three methods are used to estimate capacity requirements for different types of resources which could be used to store or shift energy for a day, a week, a year, or longer.

Timescale distribution

Although the filter method requires pre-defining the cut-off frequencies for analysis, the FIFO and LIFO methods can be applied to investigate the distribution of



(a) Energy

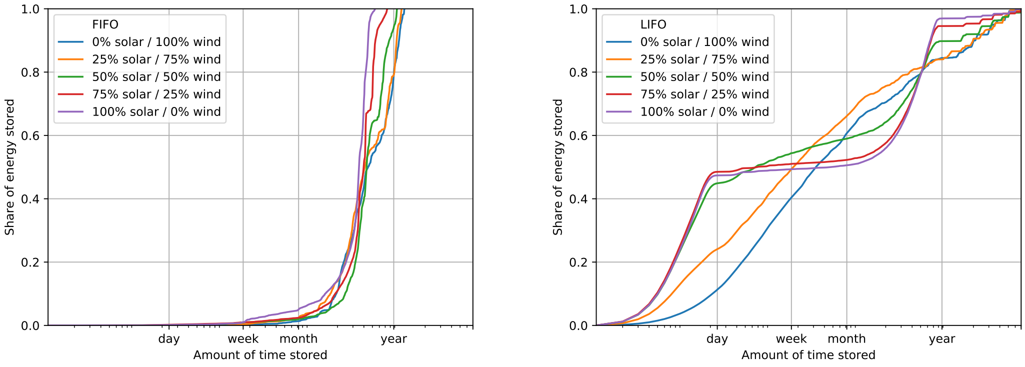


(b) Power

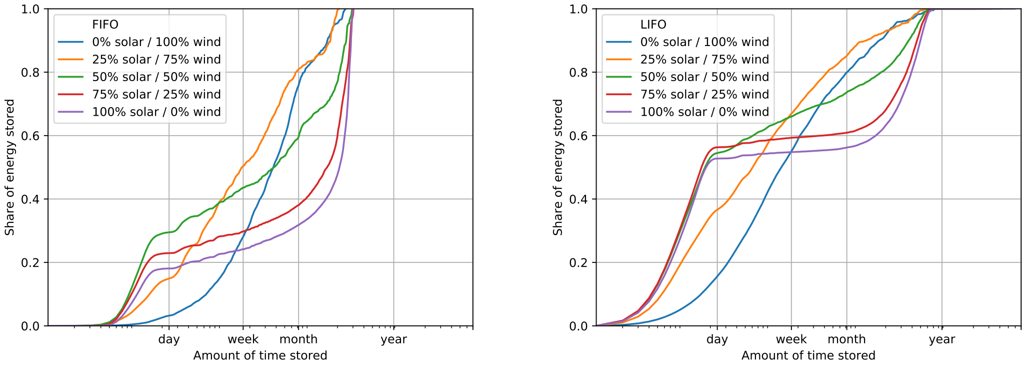
Figure 5.7: Overall storage capacity required for different solar wind ratios in the generation mix for different levels of renewable generation capacity.

possible needs.

Figure 5.8 shows the the distributions of time by which energy would need to be shifted for different solar wind ratios in the generation mix, for scenario with no (1.0x) and 20% excess generation (1.2x). In the 1.2x scenarios, generation mixes with 50% or more solar require substantial diurnal energy shifting, although energy must



(a) FIFO 1.0x **(b)** LIFO 1.0x



(c) FIFO 1.2x **(d)** LIFO 1.2x

Figure 5.8: Distribution of time scales required for energy shifting calculated using different disaggregation strategies, for different solar wind ratios, for an example case with 20% overcapacity.

also be shifted for longer durations. For generation mixes with at least 75% solar, the need for energy shifting is almost exclusively daily or interseasonal, with very little on the order of a few days or weeks. In contrast, generation mixes with at least 75% wind have a much smoother and more even distribution of energy shifting durations.

Capacity requirements

The overall requirements from Section 5.2.1 are disaggregated into requirements over daily, weekly, annual, and longer timescales for energy shifting using the three methods in Chapter 3. Each disaggregation strategy yields the required capacities for a portfolio with daily resources, weekly resources, annual resources, and flexibility resources which could shift energy for longer than one year. Each solution is viable and there are many other strategies which would yield other portfolios which could potentially meet demand. Therefore, the trends and orders of magnitude, especially those which are common across strategies, are far more important than specific values in the following results.

Figure **??** shows how the size of resources which could shift energy by up to one day varies with the solar wind mix, determined by each requirements timescale disaggregation strategy. The need to shift energy by up to one day is higher for solar dominated mixes than for wind dominated mixes, at all levels of overcapacity. For all solar wind ratios in fully variable renewable generation mixes and all amounts of overcapacity at least up to 2.0x, Great Britain would require up to 1 TWh of capacity for aggregated flexibility resources which could accomplish daily energy shifting.

For most solar wind ratios, daily energy shifting resources would need to be slightly larger in systems with some excess renewable generation capacity than in those with none. Although this initially seems counter-intuitive, it makes sense. In systems with overcapacity, more generation occurs nearer in time to demand. Therefore more energy is shifted for less than a day, while less energy is shifted for longer periods of time.

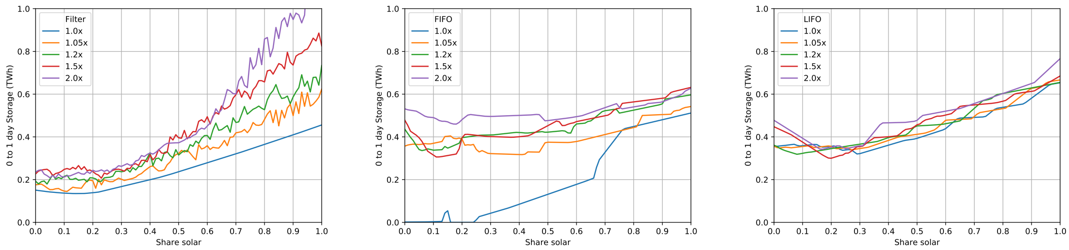
Figure **??** shows how the size of resources which could shift energy by between one and seven days varies with the solar wind mix, determined by each requirements timescale disaggregation strategy. The required capacity of resources which could shift energy by up to a week is on the order of a few terawatt-hours for all generation mixes and amounts of excess generation in fully wind and solar power systems. Wind dominated generation mixes may need slightly more energy shifting between one and seven days, although this trend is not pronounced across all strategies.

The sharp spikes instead of smooth curves are due primarily to two reasons. First, small changes in the generation mix (or demand pattern) can lead to slightly different net load profiles. For time-steps where the value of the net load was already close to zero, a small change in generation mix may mean that time-step now has excess generation instead of shortfall (or vice versa), which could affect the need for energy shifting at that time-step, especially over shorter durations.

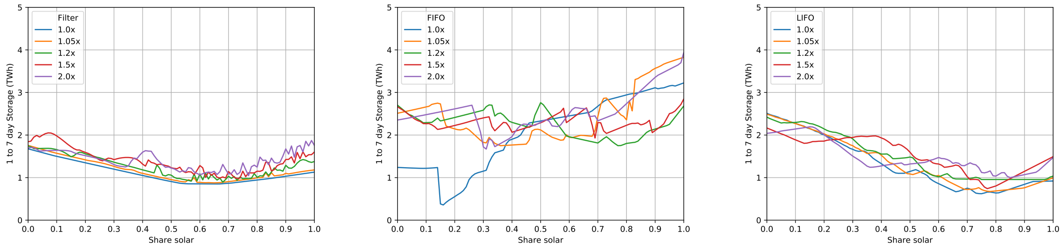
Second, this process of sorting forces each unit of energy to be in one bucket or the other, so some units of energy which are shifted for amounts of time near the cutoffs sometimes may cross the threshold from one resource to another under slightly different scenarios. This is clearly illustrated by the no overcapacity (1.0x) case in the FIFO panels of Figure 5.9 top rows, where the spike in the daily resource at 14% solar corresponds to a sharp drop in the 1-7 day resource capacity required. Realistically, that particular unit of energy could probably be shifted by approximately one day using either resource. There will be overlap between the roles and possible applications of different energy shifting technologies, which is not accounted for in this characterization of requirements.

Figure 5.9 shows how the size of resources which could shift energy by between seven days and one year varies with the solar wind mix, determined by each requirements timescale disaggregation strategy. The capacity for flexibility resources to shift energy between seven days and one year is on the order of tens of terawatt-hours for a fully renewable Great Britain. This is at least an order of magnitude greater than sizes required to shift energy by less than a week. The curves in the FIFO and LIFO panels show similar dependence on the solar wind ratio as for the aggregate flexibility capacity requirements in Figure 5.7. Wind dominated generation mixes appear particularly affected by the amount of overcapacity, which echoes the findings for aggregate flexibility capacity requirements and is explored further in Section 5.3. Together, these results imply that the aggregate flexibility capacity required is driven by energy shifting over at least weeks and potentially between seasons.

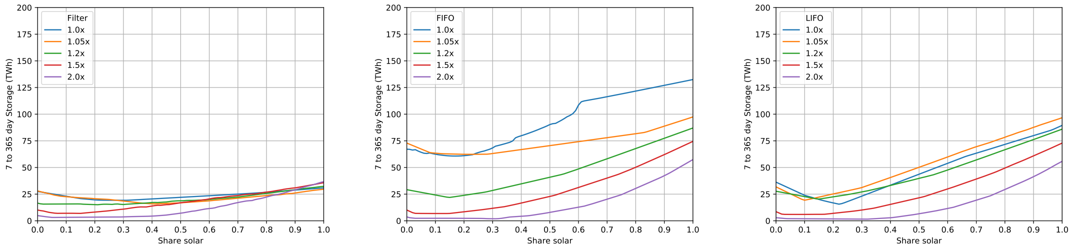
The bottom row of Figure 5.9 shows how the size of resources which could shift energy by over one year varies with the solar wind mix, determined by each requirements timescale disaggregation strategy. There is no clear trend across all three strategies. The FIFO and LIFO disaggregation strategies yield requirements for portfolios which do not need longer than annual energy shifting for most scenarios with some overcapacity, though this is explored further in Section 5.3. The filter strategy yields requirements for a portfolio which requires some inter-annual energy



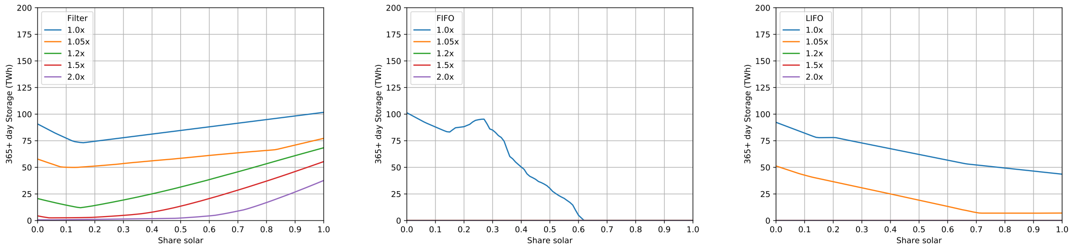
(a) Filter **(b)** FIFO **(c)** LIFO



(d) Filter **(e)** FIFO **(f)** LIFO



(g) Filter **(h)** FIFO **(i)** LIFO



(j) Filter **(k)** FIFO **(l)** LIFO

Figure 5.9: Storage capacity needed to shift energy by up to one day (top row), 1-7 days (second row), one week to one year (third row), and over one year (bottom row), estimated using three methods, for different solar wind ratios in the generation mix

shifting in all scenarios. This is expected, as this method is based on identifying regular patterns for flexibility resource cycling, which would pick up on the regular annual patterns in both demand and weather. The curves in the filter panel closely follow the relationships between aggregate flexibility capacity requirements and the solar wind ratio in Figure 5.7, implying that the aggregate flexibility capacity required is driven by this interseasonal or inter-annual energy shifting.

The distributions in Figure 5.8 could be used to illuminate how some of the larger buckets (e.g. 7-365 days or over one year here) might be utilized in practice or to select different, potentially useful cutoff durations for energy shifting. For example, for the solar dominated mixes, the 7-365 day requirement is clearly driven by the need to shift energy for a few months and not for a few weeks.

5.3 Effect of renewable generation overcapacity on temporal flexibility requirements

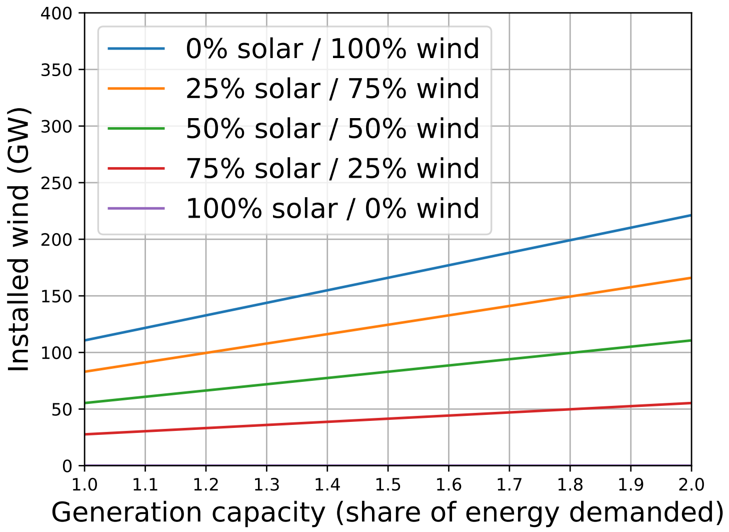
This section investigates the relationship between the amount of renewable generation capacity and the need to shift energy over different timescales, for electricity systems with 100% variable renewable generation.

One would expect renewable overcapacity to reduce the amount of energy shifting required, because the additional generation may be better temporally aligned with demand. Some demand which would be met by shifting energy through time in a scenario with no overcapacity would therefore be met with power generated at the correct time and that energy shifting capacity would not be required. Some excess generation which is not aligned with demand would be curtailed and some would still be stored (or demand shifted) to meet remaining load.

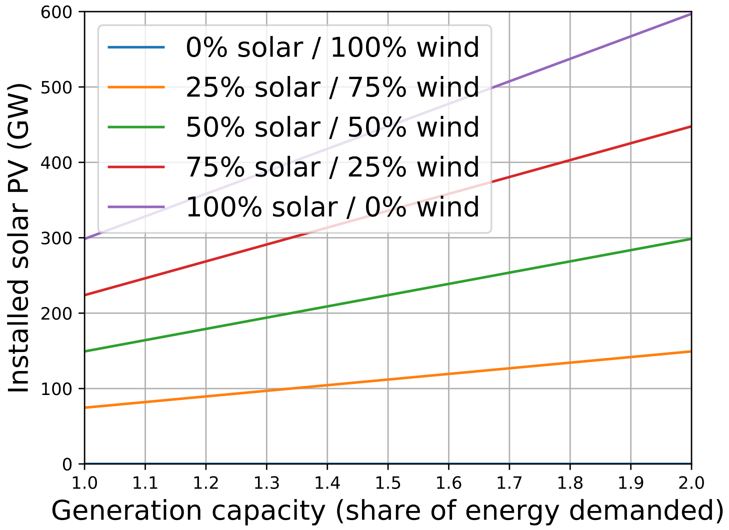
Scenarios with a range of different solar to wind ratios (0%:100%, 25%:75%, 50%:50%, 75%:25%, 100%:0%) are included in this analysis, although the effects of generation mix are analyzed in Section 5.2. For some context, the installed generation capacity which would be needed for these scenarios is shown in Figure 5.10.

5.3.1 Overall requirements

Overcapacity reduces storage energy capacity requirements for all generation mixes in Great Britain, as shown in Figure 5.11. For solar-dominated generation mixes, the greatest benefit in terms of reducing required storage size comes from the first



(a) Wind



(b) Solar

Figure 5.10: Installed generation capacity for different levels of renewable generation capacity for different solar wind ratios in the generation mix.

5% of excess generation capacity. Wind dominated mixes have larger tradeoffs between generation and storage capacity for greater amounts of overcapacity. For all generation mixes, there are eventually diminishing returns to additional overcapacity. Changes to the mix of onshore and offshore wind, weather patterns, and demand may shift optimal solar and wind ratio.

These tradeoffs between overall storage requirements and renewables overcapacity are well documented for other locations in the literature and the GB results found here are consistent with the trend that overcapacity of renewable generation significantly reduces the storage size required. For example, overcapacity of 5% (1.05x) could reduce the required storage size by nearly 50%, while overcapacity of 20% (1.2x) reduces it by approximately 80%, for a 25% solar, 75% wind mix.

The power capacity required for discharging is not significantly affected by either the generation mix or the amount of excess generation, shown in Figure 5.11. This is because there are some times with neither wind nor sunlight. If storage is the only form of flexible and dispatchable power in the system, the maximum net load sets the minimum storage power capacity because all shortfall is met by storage.

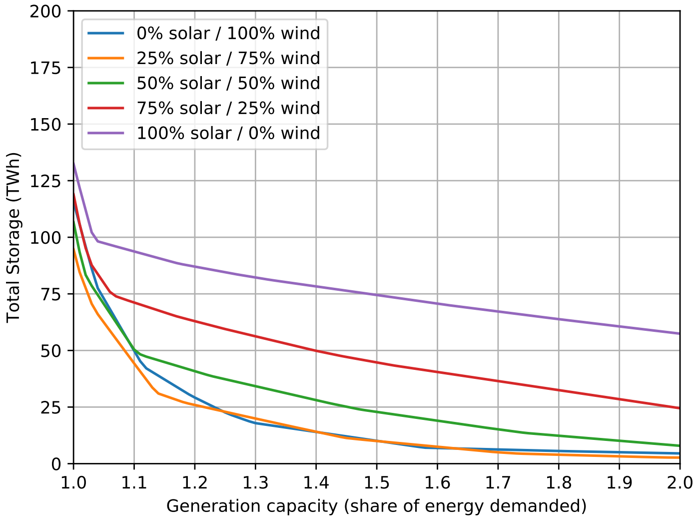
The charging power required depends on storage operation and when energy is stored or curtailed. For example, the maximum charging power could be reduced by allowing energy to be stored for longer. Systems with solar dominated generation mixes require greater charging power than with wind dominated mixes, regardless of overcapacity. This is because all demanded energy must be generated over a shorter time period during the day, while wind dominated mixes could charge more evenly during day and night.

Marginal value of renewable overcapacity

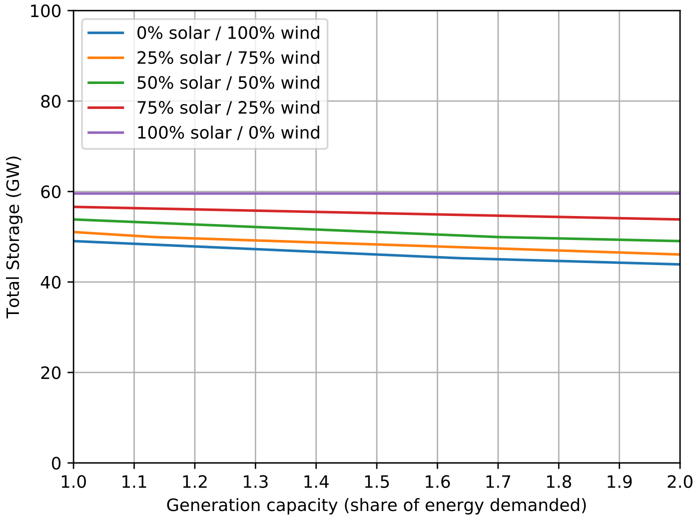
The reductions in storage capacity required are expected, as some of the additional generation will be temporally aligned with demand. Figure 5.12 shows how much additional of the additional generation is aligned with demand over the eight year simulation.

Costs

This section explores the system costs which would be associated with the tradeoffs between generation capacity and storage capacity. It shows the system configurations under which investing in renewables overcapacity or investing in more storage capacity is worthwhile from a system cost perspective. Although Figure 5.12 clearly shows potential benefits beyond 2.0x overcapacity, such high penetrations



(a) Energy

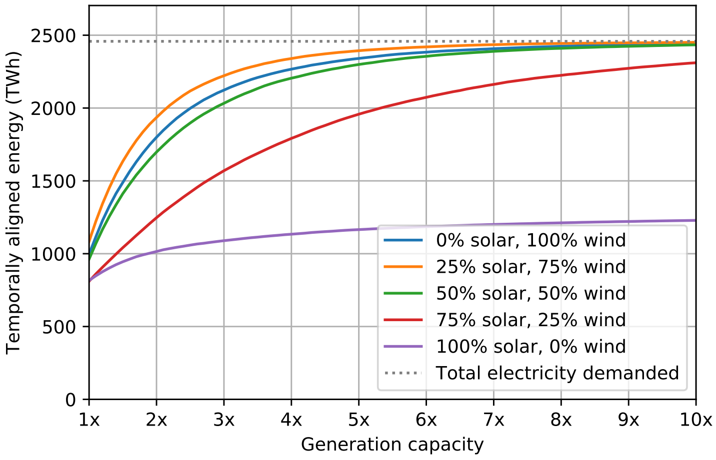


(b) Power

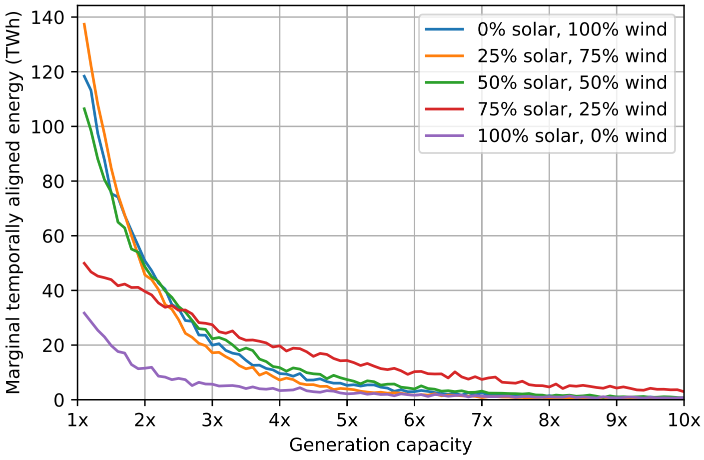
Figure 5.11: Overall storage capacity required for different levels of renewable generation capacity for different solar wind ratios in the generation mix.

of renewables were deemed unrealistic and this section focuses on costs up to 2.0x overcapacity.

The cost-optimal amounts of storage and renewable generation capacity may depend on how these technologies develop and how their costs fall relative to each other. Costs have been falling rapidly and often outstripping projections for



(a) Total



(b) Marginal

Figure 5.12: There are diminishing returns to additional renewable overcapacity in terms of additional generational temporally aligned with demand.

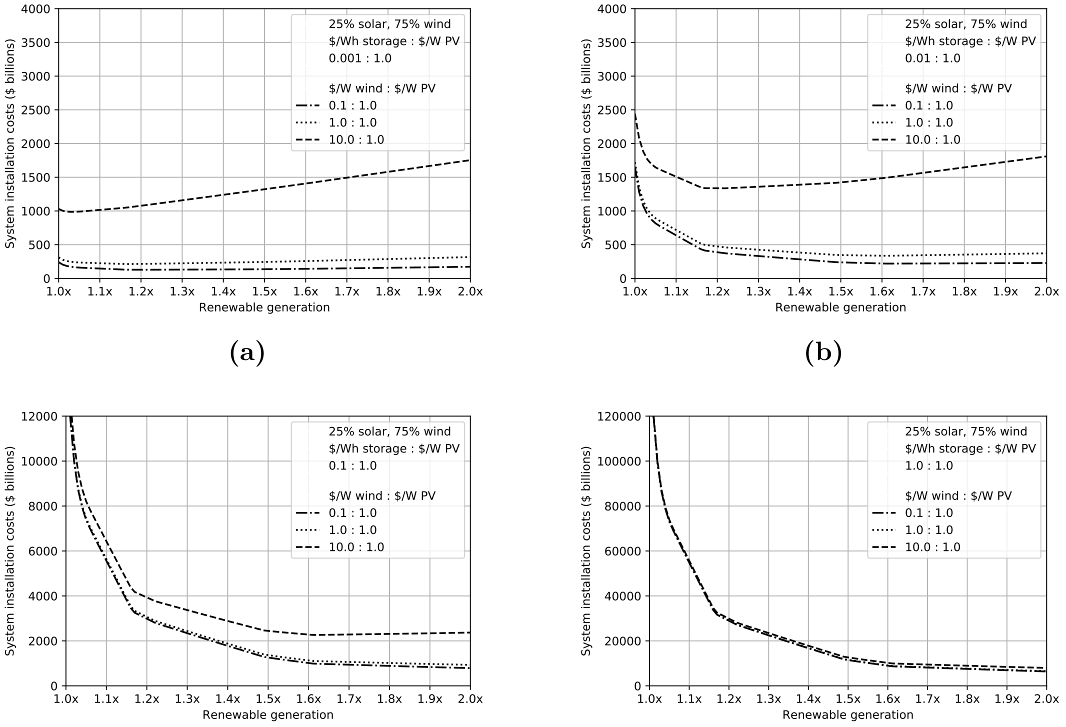
photovoltaics, onshore and offshore wind turbines, and various types of energy storage [33, 34, 35, 36]. To account for uncertainty about future costs, this analysis uses ratios between costs of storage and costs of renewable generation to show the cost-minimizing combinations of generation and storage for different relative costs.

In these simulations, all costs are reported relative to the installation cost of PV, which is set at $1000/kW [36]. Therefore, the absolute costs should not be taken as projections or estimates of actual future costs, but rather the relative values may yield interesting insights. For example, if offshore wind costs fall much more quickly than the cost of batteries, then investing in more wind generation might be even more beneficial than installing storage, even if it means curtailing more wind. The cost of solar PV was fixed while storage and wind costs varied because there is more uncertainty about technology development for different storage resources and for offshore wind. No cost was assigned to curtailment; large curtailment payments would affect optimal investment portfolios by making overcapacity more expensive relative to storage.

Total system installation cost is the sum of storage costs and generation costs, which is the amount of storage and generation installed multiplied by the relevant unit costs. This analysis uses an average unit cost per kilowatt-hour for all storage installed in the system because the specific technologies making up the overall storage portfolio are not defined. Therefore, this could be thought of as the average unit cost for flexibility in the system. Because this flexibility would be provided by a portfolio of resources with different unit costs, future work could extend this analysis to the relative costs of different flexibility assets, investigating which portfolios are optimal based on how their costs fall relative to each other.

Figure 5.13 shows total system installation costs for a wide range of relative cost combinations, using the 25% solar, 75% wind case. The cost-minimizing amount of overcapacity varies with the ratio of storage unit cost to solar PV unit cost, for different solar PV to wind cost ratios. Current battery installation costs are on the order of hundreds of US dollars per kWh and are projected to continue falling rapidly [33, 34] while other technologies, such as pumped hydropower, can be below 100 US dollars per kWh [33]. Figure 5.13c shows costs closest to those today, using \$100/kWh storage and \$1000/kW PV. If storage installation costs fall more rapidly than PV costs, the effect of overcapacity on system cost would follow a trend closer to the curves in Figures 5.13a and 5.13b; if storage costs fall less quickly than PV costs, the trend would be closer to that in Figure 5.13d.

In the United Kingdom, current costs of solar PV and onshore wind per unit installed are approximately equal, with offshore wind three to four times as expensive [36]. If offshore wind costs decline more quickly than PV costs, the 1:1 ratio for



(a) **(b)**

(c) **(d)**

Figure 5.13: Overcapacity which minimizes total system costs for different cost ratios between storage and renewable generation, for the 25% solar, 75% wind case. Note different vertical axis scales.

wind to solar costs (dotted lines in Figure 5.13) would be most realistic; if PV costs decline much more rapidly than wind costs, the 10:1 ratio (dashed lines) might be more appropriate.

Given that installing wind turbines is more expensive than solar panels, especially for offshore wind, the cost-optimal amount of excess generation would be approximately 50% (1.5x), but there are diminishing marginal returns after approximately 20% (1.2x) overcapacity. If the costs of wind fall substantially faster than the costs of solar, then the amount of overcapacity which minimizes costs is even larger.

For nearly all cost ratios, some amount of excess generation minimizes system installation costs. Although the results here have used assumed perfect efficient energy shifting, inherent inefficiency in storage makes the case for overcapacity stronger, because more storage would be needed to provide the same service. Only if the costs of storage fall substantially more quickly than the costs of generation would relying on storage with no overcapacity become cost-minimizing.

However, current economic incentives for individual investors and developers may not align with these system-optimal outcomes. Many may not choose to build extra renewable capacity if they knew it would have a lower load factor, higher curtailment, and long pay-back time to recoup their investments. There is an opportunity for policy to better align these incentives, for example through requirements for reserve capacity, co-locating storage with generation, curtailment payments, and other regulatory instruments.

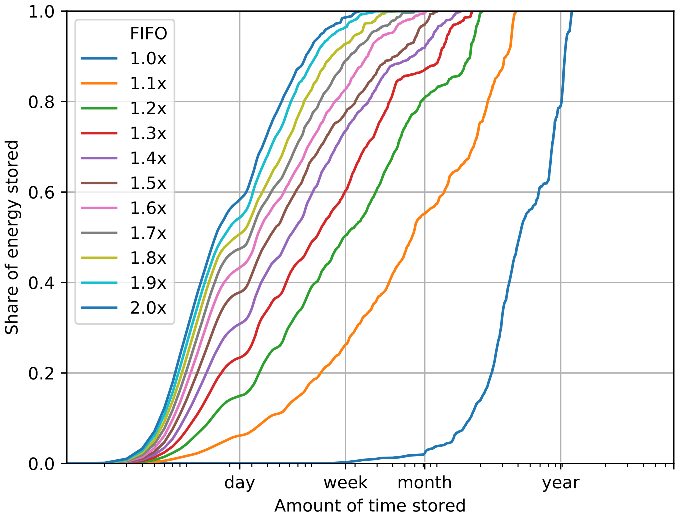
5.3.2 Requirements over different timescales

This section shows how the requirements for shifting energy over different timescales vary with the amount of overcapacity of renewable generation. The overall storage requirements in Section 5.3.1 will be met by a portfolio of storage assets with different parameters. To better understand which types of resources might be needed under different scenarios, the overall storage profiles are disaggregated using the three methods described in Chapter 3 to identify the timescales over which energy needs to be shifted and how these can inform potential asset portfolios to meet these needs.

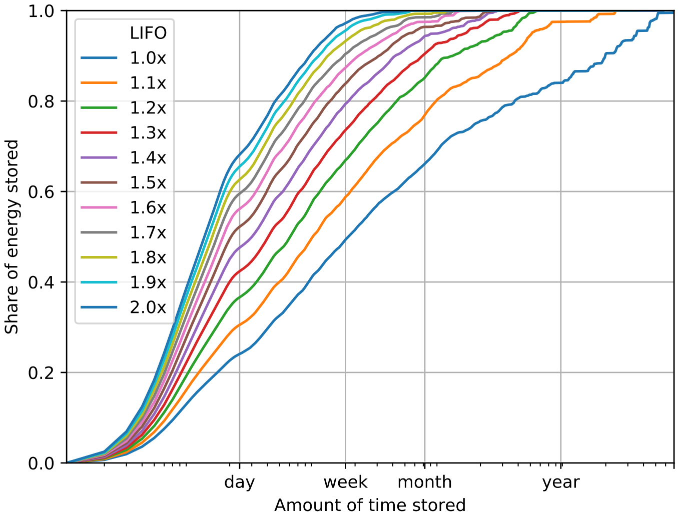
First, the FIFO and LIFO disaggregation methods are employed to investigate the distribution of timescales for which energy would need to be stored. Then, all three disaggregation strategies are used to estimated capacity requirements for different types of resources which could be used to store or shift energy for a day, a week, a year, or longer.

Timescale distribution

The disaggregation methods produce different distributions for how long energy needs to be stored. These differences are not a problem; rather they show that multiple potential asset portfolios could meet the technical energy shifting requirements, depending on how they are operated. For an example 25% solar, 75% wind case, Figure 5.14 shows the fraction of all stored energy which is stored for up to a given amount of time.



(a) FIFO



(b) LIFO

Figure 5.14: Distribution of time scales required for energy shifting calculated using different disaggregation strategies, for different levels of renewable generation capacity, for an example scenario with 25% solar and 75% wind.

These distributions could be used to understand what types of asset portfolios could meet these storage needs. For example, all of the energy stored for up to a day could be met with one type of resource (e.g. Lithium ion batteries), while energy stored for up to a week could be met by another type (e.g. pumped hydropower). Alternatively, it also shows what share of energy shifting requirements would need to be met by alternative sources of flexibility (e.g. imports, backup generation) if for example long term storage of more than one year is unavailable, infeasible, or prohibitively expensive.

Across all methods, increasing renewables overcapacity reduces the timescales required for energy storage. The share of all energy stored shifts from long term to short term. This is particularly important because clean long term energy storage technologies are not currently widely available, while renewable generation and short term storage have experienced both improved performance and falling costs in recent years.

For example, using the FIFO strategy with no overcapacity (1.0x), all of the energy stored is stored for two years or less, with 80% of that stored for eighteen months or less and less than 1% stored for a week or less, shown in Figure 5.14. In contrast, using the LIFO strategy with no overcapacity (1.0x), over 80% of the energy stored is stored for six months or less, and half of the energy stored is stored for one week or less and just over one quarter stored for one day or less. However, 10% of energy stored would need to be stored for longer than two years or met using other resources, for example dispatchable generation, interconnectors, or demand response.

With 20% excess generation (1.2x), the FIFO disaggregation method suggests all of the energy shifting needs could be met using storage of 100 days or less, with 80% stored for less than a month and about 15% stored for less than one day. The LIFO method would create a portfolio where nearly all of the energy shifting needs could be met using storage of one year or less, with nearly 90% stored for less than one month and nearly 40% stored for one day or shorter.

Because these are illustrative breakdowns of energy shifting timescales, these would satisfy demand over the entire simulation, but they do not necessarily reflect optimal or realistic storage portfolios which might be chosen. Ongoing research is investigating how these storage timescales correspond to more realistic resource portfolios and operating strategies. For example, the LIFO strategy, which requires some short term storage with high throughput and some very long term energy shifting, could align well with a portfolio of many batteries and some hydrogen storage or biogas backup generation.

Capacity requirements

This section shows the sizes of storage assets required if the overall storage needs were met by portfolios with four types of assets which could store energy for up to a day, a week, a year, and indefinitely. The different potential portfolios are referred to by the disaggregation method used to create them: filter, FIFO, and LIFO.

The resulting storage capacity requirements at these timescales for each portfolio created using the three methods are shown in Figure 5.15. Unsurprisingly, the specific sizes needed for each type of storage vary somewhat but are on the same order of magnitude across the three portfolios. More importantly the trends regarding effects of overcapacity and of solar-wind generation mix on storage sizes are similar across all three portfolios.

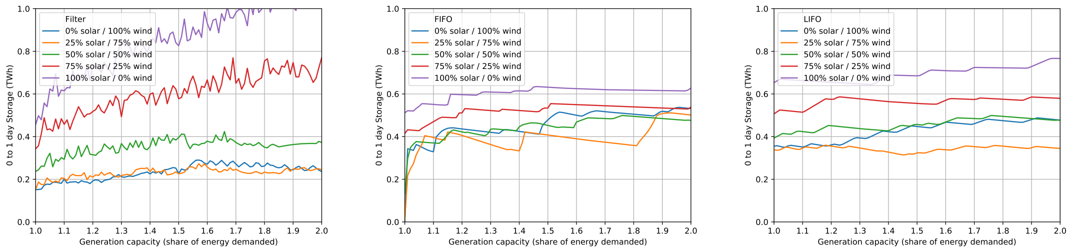
The reduction in overall storage capacity with increasing renewables overcapacity shown in Figure 5.11 is clearly driven by a reduction in the need for interseasonal (7-365 day) and interannual (>365 day) storage. Overcapacity significantly reduces the need for longest term storage, with the first 20% of renewables overcapacity making the greatest difference across all methods, but does not reduce the need for shorter term storage. Renewables overcapacity could eliminate the need to store energy for more than one year for all generation mixes and reduces the size of the 7-365 days storage asset, if portfolios were similar to those created with the FIFO and LIFO methods. Overcapacity also significantly reduces the size of interannual storage asset required for the filter portfolio, especially for the wind-dominated energy mixes. It is unsurprising that the filter-created portfolio still has some interannual energy shifting, especially for solar-heavy generation mixes, because it is constructed by identifying regular patterns which could correspond to potential charge and discharge cycle frequencies. Seasonal weather and demand patterns will appear in the net load and overall storage profile and could be harnessed with the right types of technology.

It may seem counterintuitive that overcapacity could increase the need for shorter term storage, with a slight upward trend for daily and weekly storage across all portfolios. Overcapacity reduces the need for overall storage because more electricity is generated at the times when it is demanded, so less must be stored across all assets. However, with overcapacity, some demand that would have been met by energy stored for over a year without overcapacity can be met by excess energy generated closer in time to demand and could therefore be served by a different storage asset. This is visible as distinct peaks in the third row of Figure 5.15 for the 7-365 days storage for FIFO and LIFO at the amounts of overcapacity where >365 day storage reaches zero in the bottom row.

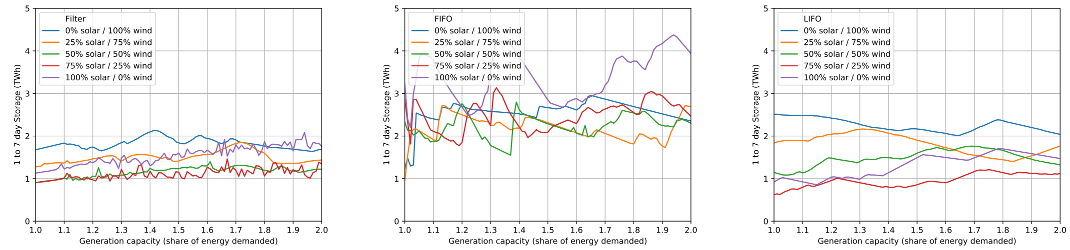
Although the daily and weekly storage assets may have smaller capacity than the interseasonal and interannual, the shorter-term storage would be much more heavily utilized. Figure 5.15 shows all three methods suggest that about half a terawatt-hour of daily storage is required, but these asset portfolios would need to be operated quite differently. This can be seen by look at how much of all stored energy would be stored for up to a day or a week in Figure 5.14. For example, in the case of 20% overcapacity (1.2x), these daily storage assets would be responsible for shifting about 40% of all stored energy in the filter and LIFO portfolios and 15% in the FIFO portfolio.

The need to store energy by up to a day could be met by less than 1 TWh of storage for all generation mixes, which could be met with batteries including potentially those in electric vehicles. Electrifying all 32 million cars in Great Britain [123] with 30 kWh batteries could yield approximately 1 TWh of storage. Although these would primarily be used for driving, there could be potential synergies if even some vehicles were equipped with smart chargers or vehicle-to-grid capabilities.

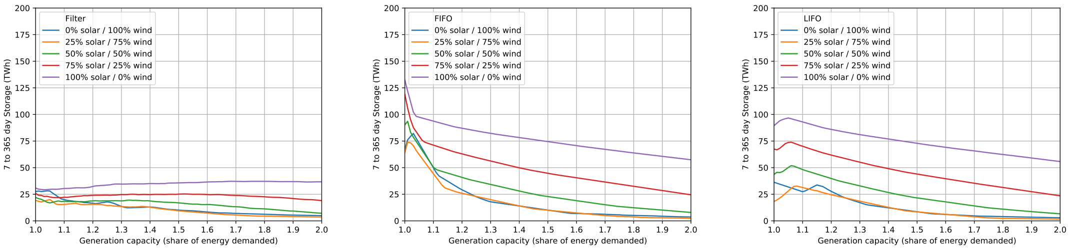
These results suggest that the most appropriate flexible resource portfolios and best operating strategy might depend on what resources a system has available. A system with lots of batteries could benefit from using a strategy similar to the LIFO method because that maximizes the amount of energy stored for the shortest periods. But such a system must account for the need to shift some



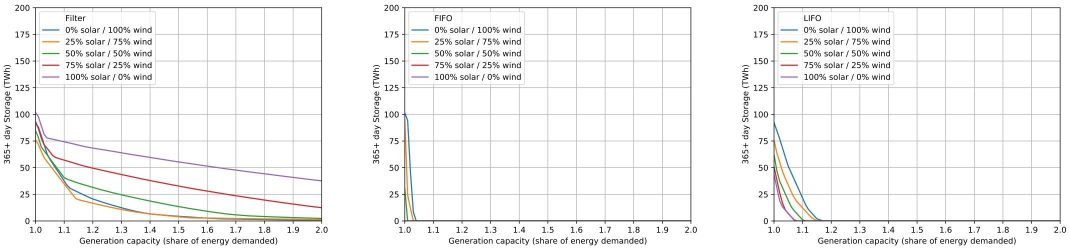
(a) Filter **(b)** FIFO **(c)** LIFO



(d) Filter **(e)** FIFO **(f)** LIFO



(g) Filter **(h)** FIFO **(i)** LIFO



(j) Filter **(k)** FIFO **(l)** LIFO

Figure 5.15: Storage capacity needed to shift energy by up to one day (top row), 1-7 days (second row), one week to one year (third row), and over one year (bottom row), estimated using three methods, for different levels of renewable generation capacity

energy over very long time horizons, for example using hydrogen or ammonia or deciding not to store that energy and instead meeting that need with imports or flexible generation paired with curtailment.

For some portfolios, it is possible that these disaggregation methods yield storage sizes for the four assets which together are larger than the overall storage capacity. This suggests that the storage resources could be used to together and may occasionally discharge into another storage device instead of only discharging to meet demand. Depending on the resources available, such a storage portfolio and operating strategy might be beneficial or it may be unrealistic especially when factoring in storage efficiency.

Analyzing the need to shift energy over different timescales means the results are not restricted to particular storage technologies. Although this paper estimates sizes for interannual storage, these energy shifting needs could instead be met by imports or flexible back up generation paired with curtailment. Indeed, overcapacity is meeting these long-term energy shifting needs through additional inflexible generation at the right times and curtailment of excess generation.

5.4 Key takeaways

This chapter addresses the question of how requirements for energy shifting in high renewable power systems depend on generation mix and system parameters. Specifically it answered the following questions for the case of Great Britain.

1. How does the share of variable renewable generation affect flexibility requirements?
2. How does overcapacity of renewables affect flexibility requirements?
3. How does the ratio of solar and wind in the generation mix affect flexibility requirements?

This chapter investigates how storage requirements over different timescales depend on generation mix and overcapacity using the case of Great Britain. The analysis uses the novel application of three methods to the problem of disaggregating overall storage requirements into short-, medium-, and long-term storage requirements, without specifying particular technology parameters or costs.

These methods include first-in-first-out and last-in-first-out control algorithms and frequency analysis using FIR filters. Specifically, they are used assess the amounts of time that energy would need to be stored for; break them down into energy stored for up to a day, a week, and year, and longer; and then estimate the associated storage capacities required for each timeframe. These results are then used to draw insights into the needs for short-, medium-, and long-term storage in fully wind and solar powered systems.

Under nearly all scenarios, if all generation if produced domestically, some long duration energy shifting is required. This may or may not be met by storage. It could be met by additional generation and curtailment of excess renewables.

Alternatively, power generation could take place outside of Great Britain and then be imported. This might involve interconnection with other regions, utilizing spatial flexibility instead of temporal flexibility. Great Britain already has operational interconnectors with Ireland and mainland Europe, with more planned. Although not yet a widespread practice, it could involve importing hydrogen or ammonia (or another hydrogen carrier or fuel) which has been created elsewhere. To be compatible with climate goals, the power-to-gas processing should use renewable generation in another location, such as solar in the Sahara or the Middle East or geothermal in Iceland.

As expected, flexibility requirements over all timescales increase with the share of VRE in the system. Systems with even 20% VRE need the ability to shift energy by up to a day, while the need to shift energy by more than one week only affects systems with more than 50% VRE. Depending on the generation mix and the resource portfolio available, it may be possible to have a system with up to 95% VRE without the need to shift energy for longer than one year.

In fully wind and solar powered systems, there is always a need for some interseasonal energy shifting, on the order of tens of terawatt-hours for Great Britain. Although this study estimates the size of storage assets which could meet this need, these long-term energy shifting needs could be met using other resources, including imports or flexible generation paired with additional curtailment of renewables. Solar-dominated generation mixes in Great Britain would require more interseasonal energy shifting than wind-dominated mixes, though this would change for other locations with different weather and demand patterns.

Overcapacity of 20% could potentially eliminate the need for interannual energy shifting and significantly reduce interseasonal storage sizes required, but does not reduce the need to store energy for up to a week, for all generation mixes. The need to shift energy for the longest periods of time is significantly reduced by overcapacity because more energy is generated closer to the time to when it is demanded. Given that clean long term energy storage technologies are not currently widely available and that renewable generation and short-term storage are getting cheaper while improving performance, overcapacity could enable the energy system to meet demand in fully wind and solar powered systems using only existing storage technologies.

For all generation mixes, the daily storage required is between half and one terawatt-hour. Depending on how these storage assets are operated, this could account for up to 40% of all energy stored for a system with 20% overcapacity, although it would be only about 1% of the size of the overall energy storage required. This suggests that short term storage needs could be met by assets with much higher throughput and power-to-energy ratios than long-term storage needs.

Disaggregating overall storage requirements into the need for energy shifting over different timescales can be used to show how these needs could be met by portfolios with different types of storage assets. For example, if most assets available had relatively high self-discharge, one strategy might want a strategy to maximize the amount of energy stored for the shortest amounts of time. The LIFO strategy requires mostly daily and weekly storage with high throughput, but it also requires some interseasonal and interannual energy shifting. This could align well with a portfolio of mostly batteries, in combination with hydrogen storage or flexible biogas generation with curtailment to address the long-term storage needs.

Due to avoided storage costs, overcapacity of renewables is cost effective for all system configurations and cost assumptions. For storage to generation cost ratios of greater than 0.01 $/Wh storage to 1 $/W PV, up to 20% excess generation provides the greatest returns, with the marginal value of excess generation diminishing beyond this point. This analysis uses relative costs of technologies to ensure the conclusions are robust to a range of potential cost trajectories that spans four orders of magnitude.

Only if the costs of storage fall precipitously would relying on storage become cost-minimizing from a system perspective. Furthermore, this analysis has assumed 100% efficient storage (with an analysis of efficiency effects in Appendix A.5) and using realistic efficiencies would require greater storage capacities, making the case for overbuilding renewables even stronger. However, policy or regulatory action would be required to achieve this, because the current system provides little incentive for investors and developers to build excess renewable capacity.

6

Flexibility requirements with potential future demand

This chapter investigates how temporal flexibility requirements could depend on demand patterns, especially due to the effects of electrifying vehicles and heating. Electricity demand in the future, by the time a more renewable and decarbonized electricity system is realized, will likely be different from demand patterns today. Although these future demand patterns are uncertain, several plausible future demand scenarios can be created using existing and likely continuing trends. In the past five years, there have been increases in EV uptake, electrifying heating to achieve decarbonization goals, digitalization and proliferation of "smart" connected devices, and efficiency gains. These trends could not only increase or decrease overall demand, but also change the times of peak demand. Furthermore, many of these demand side assets could potentially be used to help address flexibility needs in a more renewable system.

Therefore to address the question of how could temporal flexibility requirements change under potential future scenarios, this chapter addresses the following sub-questions:

1. How could electrifying cars affect the need for flexibility?

2. How does the degree of flexibility of EV charging affect remaining flexibility needs?
3. How could electrifying domestic space heating affect the need for flexibility?
4. How does the degree of flexibility of electric heating affect remaining flexibility needs?

As noted in the Chapter 1, this chapter looks only at additional demands from electrifying cars and from domestic heating, and not from other potential shifts in electricity demand. These two additional demands were chosen because of their potential to significantly increase and alter the shape of electricity demand. Electrification of vehicles is already underway and growing rapidly and electrification of at least a portion of heating demand is a realistic possibility for decarbonization. The flexible EV charging considered is unidirectional; using the EV batteries as additional storage devices for vehicle-to-grid is beyond the scope of this work.

When testing these different EV and electric heating parameters, simulations were run for generation mixes with only wind and solar power. Part of the rationale for electrifying these demands is the move away from fossil fuels to enable decarbonization of the economy. This decarbonization will only occur if the electricity is itself generated from clean sources, with wind and solar generation (not nuclear) being the fastest growing and cheapest options.

Hence, the trend of capacity requirements of flexible resources varies with deployment of EVs and electric heating, and specifically which trends hold across all generation mixes and which ones are dependent on the future generation mix will be explored. To help understand which results hold across a range potential future systems in which the EVs or electric heating might be deployed, simulations, developed in Chapter 3, were run for a range of solar wind ratios and with varying degrees of overcapacity to test how these additional demands interact with the generation mixes.

For EVs and then for electric heating, the analysis first shows how flexibility requirements change with fixed additional demands under a variety of potential scenarios. This enables examination of the sensitivity of flexibility requirements to various assumptions, for example the rate of electrification or whether individual assets are controlled in a coordinated fashion.

The analysis examines the effects if additional demand is somewhat flexible, rather than fixed. While additional demand may mean additional flexibility is required, some of that flexibility could be provided by those additional demand-side assets. This analysis examines how much flexibility could be provided by these assets and the corresponding effects of different assumptions and scenarios on the remaining system flexibility. Although the specific capacity requirements may depend on the operation or dispatch of these resources, these results show a credible potential based on the assumptions in Chapter 3.

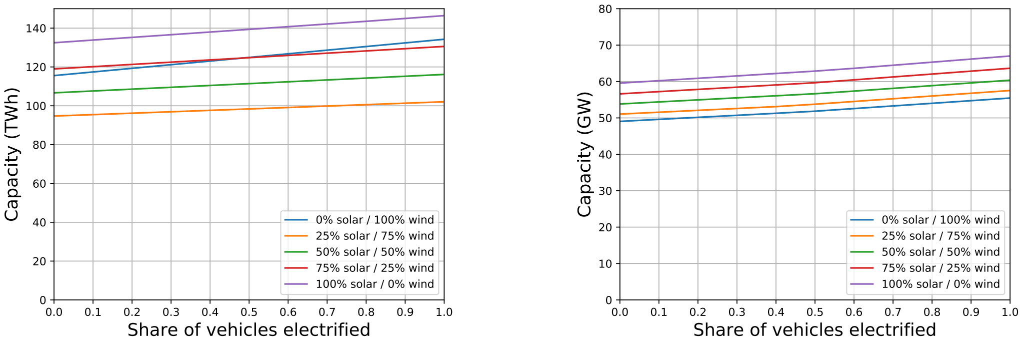
6.1 Effects of EV charging on overall flexibility requirements

This section examines the effects of adding demand from charging electric vehicles on remaining flexibility requirements. First, the effects of additional demand from electrifying vehicles without demand flexibility are investigated in Section 6.1.1. The, the effects of additional demand from electrifying vehicles with demand flexibility are investigated in Section 6.1.2. The impact of making some of that heating demand flexible on remaining flexibility needs is discussed in Section 6.1.3. Finally, Section 6.1.4 analyzes how the degree of flexibility in terms of how many hours demand could be shifted for would affect remaining flexibility requirements.

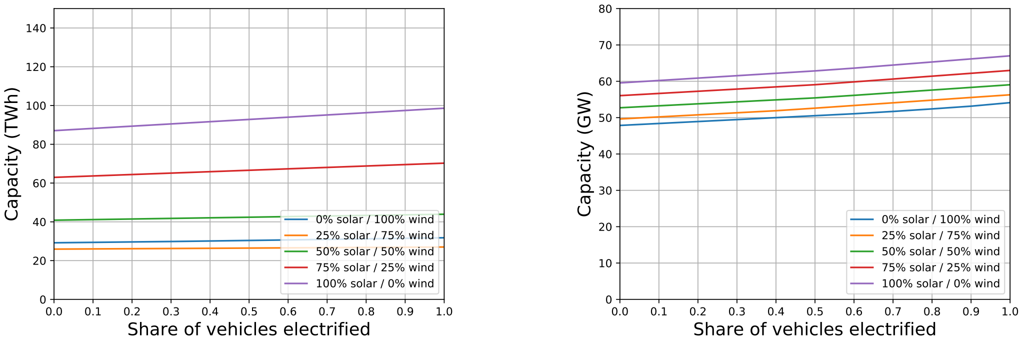
6.1.1 Penetration of inflexible EVs

Figure 6.1 shows how the flexibility requirements would vary with increasing the penetration of electric vehicles, if all the EV charging was inflexible.

The additional demands mean that both the energy capacity and power capacity required from flexibility resources would increase. This is expected because unless the generation is completely temporally aligned with the additional EV charging demand, then simply having additional demand to meet with flexible resources would mean that more energy would be in storage or displaced in time at any given time. This can be seen in the the different rates of increase in the energy capacity required for the generation mixes in the 1.0x case, with the steeper curves for fully wind or fully solar being less temporally aligned with the additional demand therefore needing more capacity per additional vehicle than the generation mixes with both solar and wind.



(a) Energy 1.0x **(b)** Power 1.0x



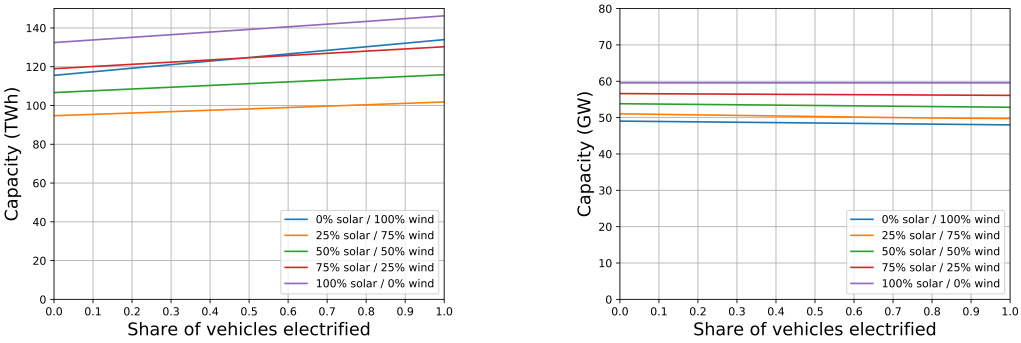
(c) Energy 1.2x **(d)** Power 1.2x

Figure 6.1: Overall storage energy (left) and power (right) capacity required depends on penetration of EVs. The horizontal axis shows the share of vehicles electrified and all EV charging is inflexible. Results are shown for simulations with 1.0x (top) and 1.2x (bottom) generation capacity.

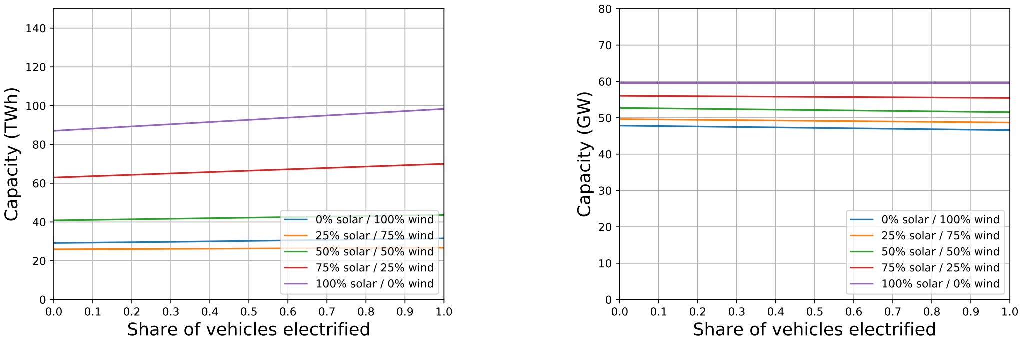
6.1.2 Penetration of flexible EVs

Figure 6.2 shows how the remaining requirements would vary with increasing penetration of EVs, if all EVs supported flexible charging. For these simulations, flexible means EV charging can be shifted by up to 24 hours before or after the time the EV would ideally be charged. The effects of that the flexible time window are explored in Section 6.1.4

The energy capacity requirements still increase with the penetration of EVs, but the power requirements do not increase if the EV charging is flexible. This result is consistent with the findings from Crozier et al. about the opportunity for smart charging to mitigate the impact of EVs on transmission and distribution systems [109].



(a) Energy 1.0x **(b)** Power 1.0x



(c) Energy 1.2x **(d)** Power 1.2x

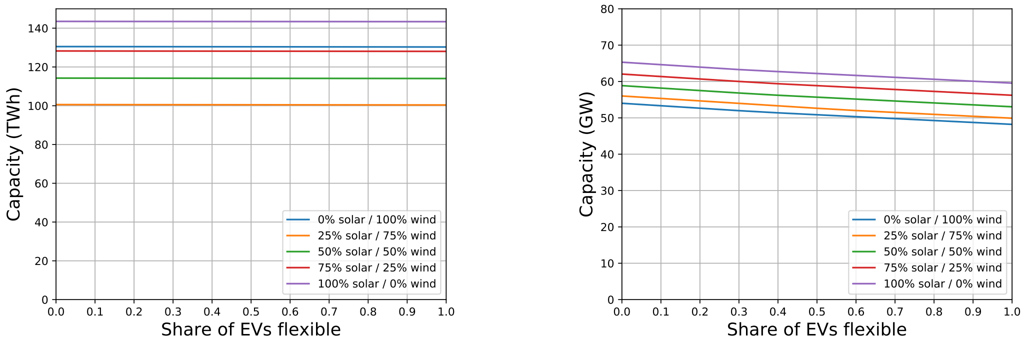
Figure 6.2: Overall storage energy (left) and power (right) capacity required depends on penetration of EVs. The horizontal axis shows the share of vehicles electrified and all EV charging is flexible. Results are shown for simulations with 1.0x (top) and 1.2x (bottom) generation capacity.

6.1.3 Share of EV charging which is flexible

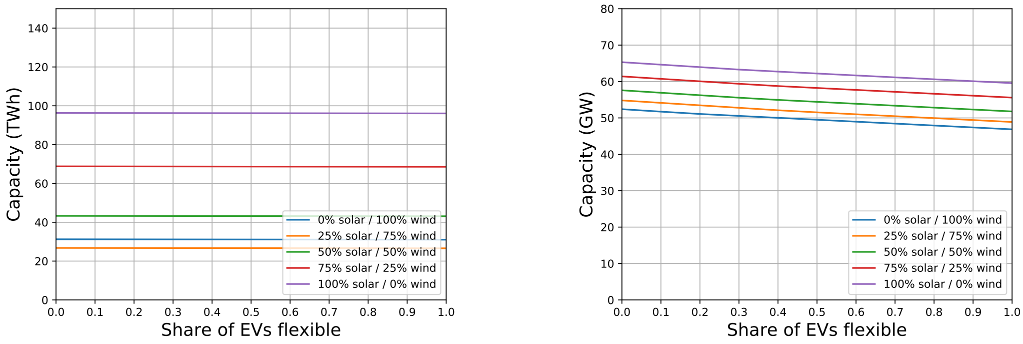
It is also worthwhile explore the scenario where most vehicles are electrified, but not all could be charged flexibly due to technical constraints or user preferences.

Figure 6.3 shows how the share of EVs which are flexible affects the energy and power requirements for simulations where 80% of the UK domestic vehicle fleet is electrified. Again, here flexible means EV charging can be shifted by up to 24 hours in either direction.

The energy capacity required does not change significantly with a greater share of EVs able to charge flexibly, at least up to 24 hours. The power capacity required decreases linearly with the share of vehicles which are able to charge flexibly.



(a) Energy 1.0x **(b)** Power 1.0x



(c) Energy 1.2x **(d)** Power 1.2x

Figure 6.3: Overall storage energy (left) and power (right) capacity required depends on the share of EVs charging which is flexible. The horizontal axis shows the share of EVs charging which is flexible, for scenarios where 80% of vehicles are electrified. Results are shown for simulations with 1.0x (top) and 1.2x (bottom) generation capacity.

6.1.4 Degree of flexibility of EV charging

This section examines the impact of the degree of flexibility of EV charging demand on the remaining flexibility requirements. As described in Chapter 3, the degree of flexibility here means the time by which the EV charging demand can be displaced, so 12 hours on the horizontal axis means that EV charging could happen up to 12 hours before or up to 12 hours after the ideally demanded charging time.

Figure 6.4 shows how the amount of time that charging is flexible for affects the energy and power capacity requirements of remaining flexible resources.

The energy capacity requirements are not significantly affected by the amount of time flexible, at least up to a day in each direction. This is fully consistent with the values in Figure 6.3.

The power capacity required depends on the amount of time by which EVs could be flexible. In particular, shifting EV charging up to four hours in either direction can reduce the remaining required power capacity for flexible resources by 5-8 GW[1] depending on the generation mix. The greatest marginal impact comes from shifting EV charging demand by up to 2 hours in each direction, which can reduce the remaining power capacity requirements by 3-5 GW, depending on the generation mix.

Shifting charging of the aggregated fleet by more than four hours in either direction does not bring significant additional benefits. These results hold for the aggregated fleet of EVs. Of course, social practices and constraints may mean that individual EVs may prefer to shift charging by more than four hours, for example waiting until the evening instead of shifting to the middle of the day because the driver is at work. This could be accommodated in the aggregated EV shifting. For example, consider the situation with three flexible EVs with the same state of charge, where in the inflexible profile A would ideally starting charging at hour 0, B at hour 4, and C at hour 8. Delaying each of these by four hours (A at 4, B at 8, C at 12) has the same aggregated effect on the overall power profile as delaying A by 12 hours and not delaying the other two (B at 4, C at 8, A at 12).

Further analysis found that increasing the degree of flexibility by up to a week in either direction also did not affect the remaining overall energy or power capacity

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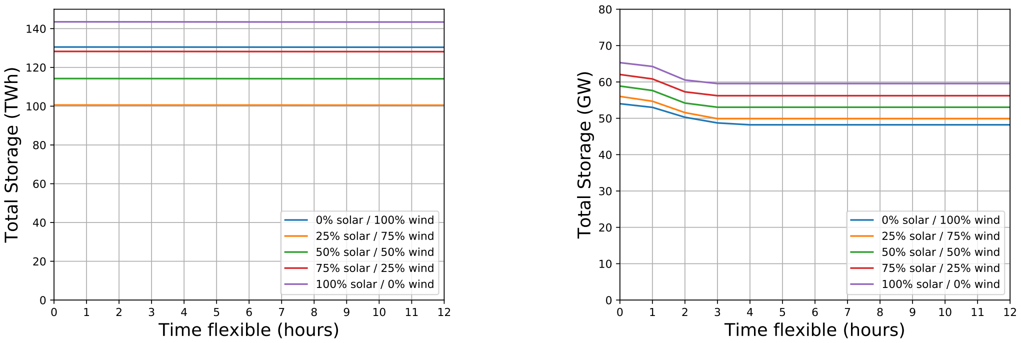
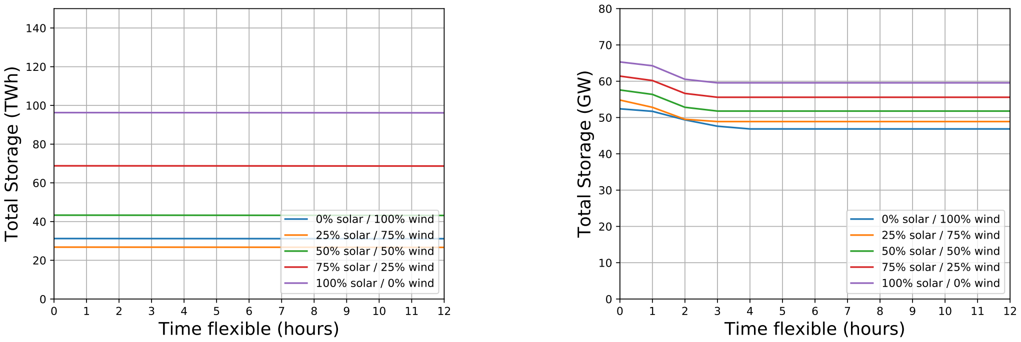
[1] These values are on a reasonable order of magnitude. If the UK has 32 million cars, 80% are electric, and they all charge using standard slow 3 kW chargers, that would yield 76.8 GW. They would never have all charged at the same time, but a figure on the order of 10% of this is plausible.



(a) Energy 1.0x **(b)** Power 1.0x



(c) Energy 1.2x **(d)** Power 1.2x

Figure 6.4: Overall storage energy (left) and power (right) capacity required depends on the degree of flexibility of EV charging. The horizontal axis shows the maximum amount of time by which EV charging could be displaced, for scenarios where 80% of vehicles are electrified and all support flexible charging. Results are shown for simulations with 1.0x (top) and 1.2x (bottom) generation capacity.

requirements. Extending the flexible time window further was not tested, as this was deemed unlikely to be compatible at scale with the social practices and vehicle usage patterns underlying the assumptions about the inflexible EV charging profile.

The flexible EV charging profile aimed to flatten the load, which meant moving charing away from peak times. A different flexible charging operational strategy may not achieve the same results of reducing the required power capacity of remaining flexibility resources.

Additionally, these results depend on using an inflexible charging profile based on the "uncontrolled" profile from Crozier et al. [107], which is based on UK National Travel Survey data and assumes charging at home. Using a different inflexible profile, for example one which allowed EV charging away from the home, could yield different results in terms of the number of hours of shifting with greatest marginal impact. As this is becoming increasingly likely to be a substantial portion of EV charging, future work could investigate how robust the results are to charging assumptions.

6.2 Effects of electric heating on overall flexibility requirements

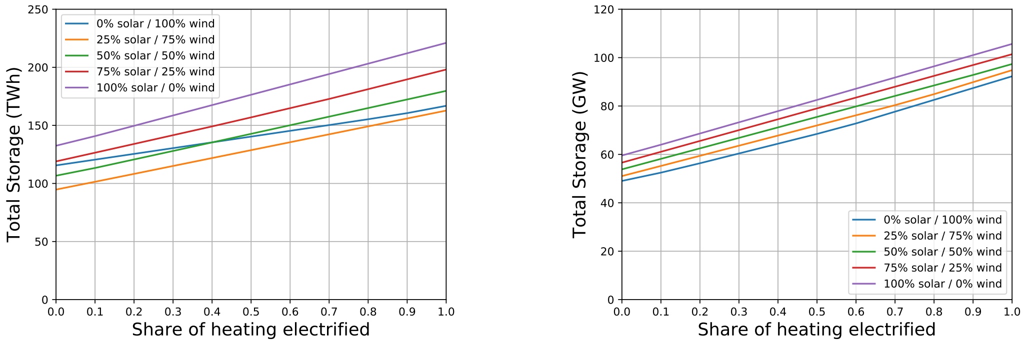
This section examines the effects of demand from electric heating on remaining flexibility requirements. First, the effects of additional demand from electrifying heating using heat pumps without demand flexibility are investigated in Section 6.2.1. Then, the effects of additional demand from electrifying heating with demand flexibility are investigated in Section 6.2.2. The impact of making some of that heating demand flexible on remaining flexibility needs is discussed in Section 6.2.3. Finally, Section 6.2.4 analyzes how the degree of flexibility in terms of how many hours demand could be shifted for would affect remaining flexibility requirements.

6.2.1 Penetration of inflexible electric heating

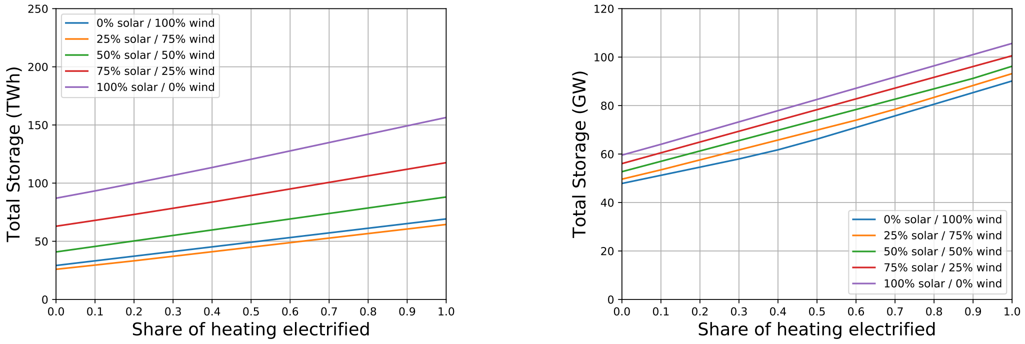
Electrifying heating without any form of demand flexibility would be expected to change the need for system flexibility, although by how much would depend on the generation mix and other system parameters. Electrifying heating increases demand, particularly in winter. Additional generation would be needed to account for this demand, but the need for flexibility depends on how temporally aligned this additional generation and the heating demand are.

Figure 6.5 shows how adding electric heating demand to existing historical demand could affect the minimum energy and power capacity requirements for flexible resources, under scenarios with different generation mixes.

This is entirely expected for power requirements, because adding inflexible heating demand increases the peak demand and there will still be some times without wind or sunlight during which flexible resources would be utilized to meet all demand.



(a) Energy 1.0x **(b)** Power 1.0x



(c) Energy 1.2x **(d)** Power 1.2x

Figure 6.5: Overall storage energy (left) and power (right) capacity required depends on penetration of electric heating. The horizontal axis shows the share of heating electrified and all electric heating is inflexible. Results are shown for simulations with 1.0x (top) and 1.2x (bottom) generation capacity.

In terms of energy, it is also not surprising that additional heating demand increases the required size of energy shifting resources. Unless the generation is completely temporally aligned with the additional heating demand, then simply having additional demand to meet with flexible resources would mean that more energy would be in storage or displaced in time at any given time.

The degree of how much this additional demand would increase the need to shift energy through time depends on the alignment between generation and demand. Therefore, one would expect the share of electric heating to affect the size of flexible resources needed differently for different generation mixes. It is clear that the wind dominated energy mixes require significantly less capacity to shift energy through time than the solar dominated mixes. This aligns with expectations, as the UK experiences windier weather in winter than in summer, leading to more wind power available at the same times as heating demand.

6.2.2 Penetration of flexible electric heating

Figure 6.6 shows how the remaining requirements would vary with increasing penetration of heating electrification, if all electric heating could be flexible. For these simulations, heating demand was assumed to be flexible up to three hours in either direction. The effects of this assumption about the size of the flexibility window are investigated Section 6.2.4.

As expected, the energy capacity needed for remaining flexible resources increases with the penetration of electric heating flexible up to 3 hours, just as it did for the penetration of inflexible electric heating.

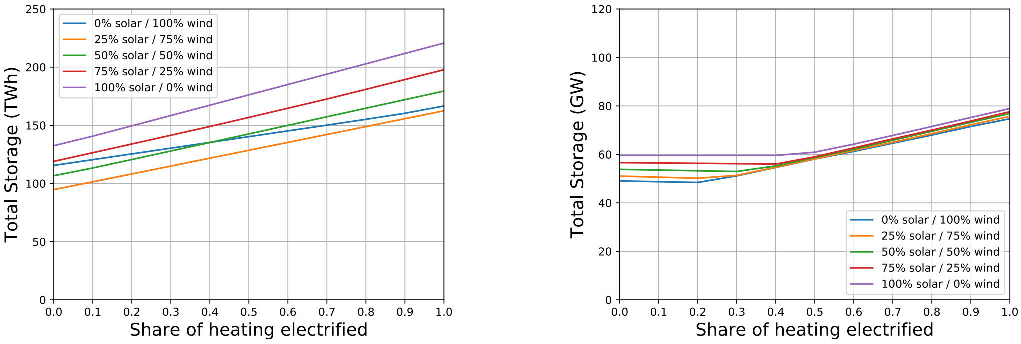
The power capacity needed for remaining flexible resources is more interesting in the way that it depends on the penetration of flexible electric heating. If all of the electric heating were flexible by up to 3 hours, then 20% to 50% of UK domestic heating could be electrified without increasing the need for additional power capacity of flexible resources in a fully wind and solar system. However, for greater shares of heating electrified, the need for additional power capacity in flexible resources increases linearly with the penetration of electric heating.

Systems with solar dominated generation mixes could absorb slightly greater shares of electric heating before needing to increase the power capacity of their flexible resources; however, this is because they needed flexibility assets with greater power capacity without electric heating.

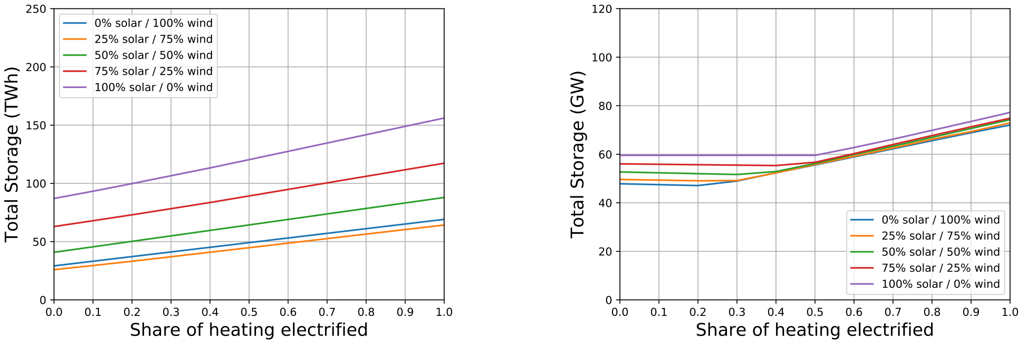
6.2.3 Share of electric heating which is flexible

It is also worthwhile explore the scenario where most domestic heating is electrified, but not all could be charged flexibly due to technical constraints or user preferences.

Figure 6.7 shows how the share of heating which is flexible affects the energy and power requirements, for simulations where 80% of the UK domestic housing



(a) Energy 1.0x **(b)** Power 1.0x



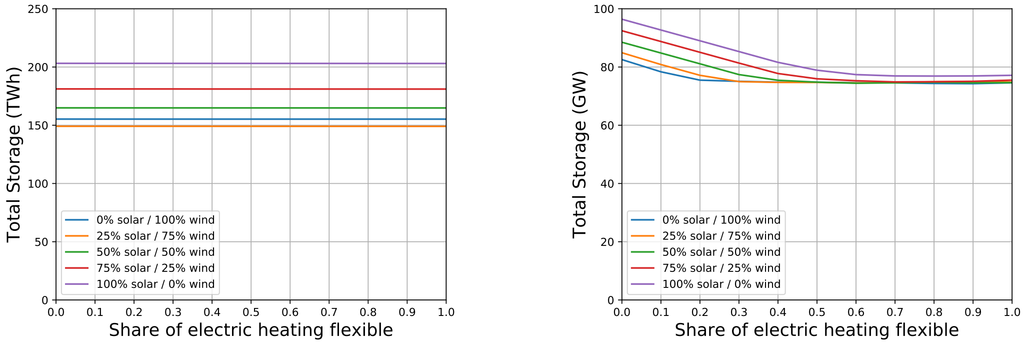
(c) Energy 1.2x **(d)** Power 1.2x

Figure 6.6: Overall storage energy (left) and power (right) capacity required depends on penetration of electric heating. The horizontal axis shows the share of heating electrified and all electric heating is inflexible. Results are shown for simulations with 1.0x (top) and 1.2x (bottom) generation capacity.

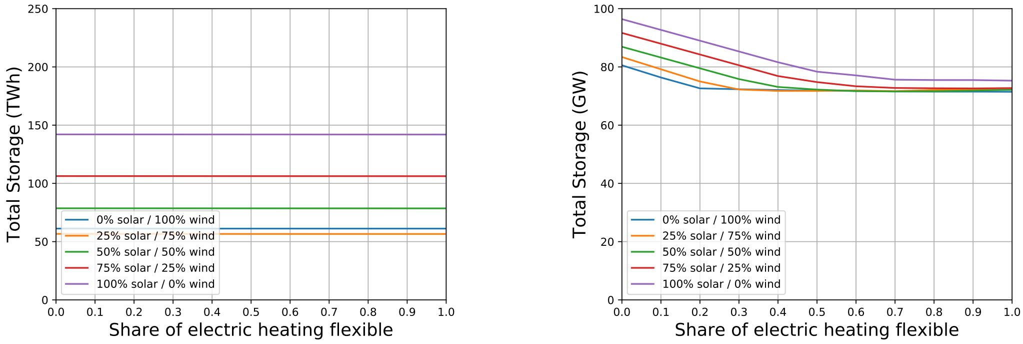
stock has electric heating. Again, here flexible means electricity use for heating can be shifted by up to 3 hours in either direction.

The energy capacity required does not change significantly with a greater share of heating able to charge flexibly, at least up to 3 hours.

Increasing the share of flexible heating can reduce the power capacity required from remaining flexibility resources by 8-21 GW, depending on the generation mix. The power capacity required decreases linearly with the share of flexible heating up to a point (around 30% flexible for a 25% solar 75% wind generation mix), after which increasing the share of heating which is flexible has no more effect. Only a fraction of the domestic heating would need to be flexible to yield most of the benefits in terms of power capacity required.



(a) Energy 1.0x **(b)** Power 1.0x



(c) Energy 1.2x **(d)** Power 1.2x

Figure 6.7: Overall storage energy (left) and power (right) capacity required depends on the share of electric heating which is flexible. The horizontal axis shows the share of flexible electric heating, for scenarios where 80% of heating is electrified. Results are shown for simulations with 1.0x (top) and 1.2x (bottom) generation capacity.

6.2.4 Degree of flexibility of electric heating

This section examines the impact of the degree of flexibility of electric heating demand on the remaining flexibility requirements. As described in Chapter 3, the degree of flexibility here means the time by which the heating demand can be displaced, so 6 hours on the horizontal axis means that electricity use for heating could happen up to 6 hours before or up to 6 hours after the originally demanded time.

As expected, Figure 6.8 shows that the amount of time by which heating demand is flexible can have an impact on the power capacity requirements, but not on the energy capacity requirements of remaining flexible resources.

The greatest impact comes from shifting demand heating demand by up to 2-3 hours, depending on the generation mix, but shifting heating demand by even up to one hour could have a significant impact on the power capacity needed, with 9-19 GW of power capacity avoided depending on the generation mix.

Further reductions in power capacity can be achieved by allowing heating demand to be flexible for up to 12 hours, with diminishing marginal returns for each additional hour of flexibility. Flexibility of greater than 12 hours was not tested; this was deemed to not make sense due to diurnal temperature patterns, social practices, and the UK building stock.

These results are based on using an inflexible profile from Watson et al. [111], which uses a mix of air-source and ground-source heat pumps. Using a different inflexible or ideal heating profile could yield different results about the number of hours of shifting with the greatest impact on remaining flexibility requirements.

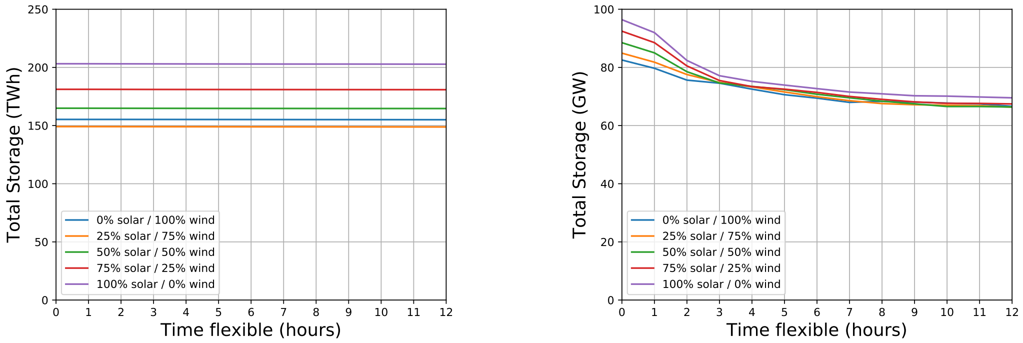
6.3 Key takeaways

This chapter has examined how flexibility requirements could depend on additional demand from electrifying domestic vehicles and heating in the UK.

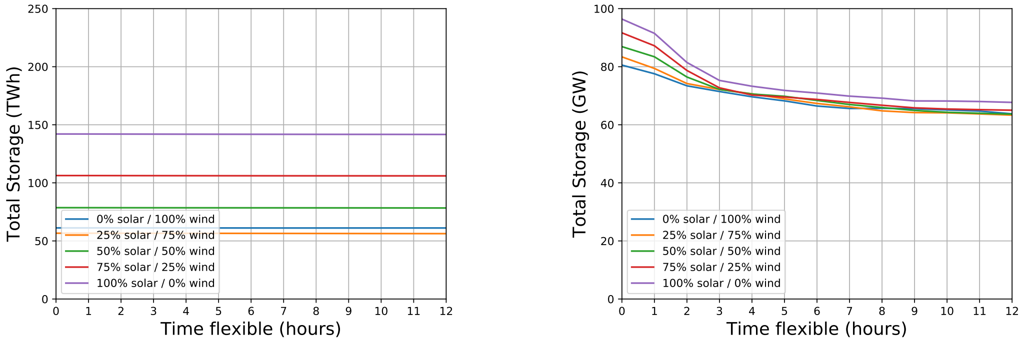
To address sub-question 1, increasing the penetration of electric vehicles increases the energy capacity of flexible resources required, but any additional flexible power capacity required depends on the degree of flexibility of the EVs.

For EVs, increasing the electrification rate with EVs which can charge flexibly does not increase the power capacity requirements of remaining flexible resources. The power capacity of remaining flexibility resources would decrease linearly with the share of those EVs which could charge flexibly.

To address sub-question 2, the degree of flexibility of EVs affects the power capacity requirements of flexible resources, but not affect the energy capacity required. The greatest impact comes from shifting EV charging by up to 2 hours away from the originally scheduled charging time. Flexibility of more than 4 hours in either direction for the aggregated EV fleet does not bring significant additional benefits in terms of flexible resource power capacity avoided. These results are



(a) Energy 1.0x **(b)** Power 1.0x



(c) Energy 1.2x **(d)** Power 1.2x

Figure 6.8: Overall storage energy (left) and power (right) capacity required depends on the degree of flexibility of electric heating. The horizontal axis shows the maximum amount of time by which electric heating could be displaced, for scenarios where 80% of heating is electrified and all support flexible charging. Results are shown for simulations with 1.0x (top) and 1.2x (bottom) generation capacity.

based on the inflexible "uncontrolled" charging profiles from Crozier et al. [107]; using a different inflexible or ideal charging profile could change the number of hours of shifting with the greatest impact.

To address sub-question 3, increasing the penetration of electric heating increases both the energy capacity and power capacity required of flexible resources, even if some of that electric heating is flexible. Depending on the generation mix, 20%-50% of UK homes could be electrified with heating that is flexible by up to 3 hours without increasing the power capacity required for remaining flexible resources. However, greater penetration of electric heating would require larger power capacity of remaining flexibility resources.

If 80% of UK housing stock heating were electrified, the power capacity of remaining flexibility resources would decrease linearly with the share of heating which is flexible, up to a point after which having more flexible heating does not have an impact on the power requirements. For a 25% solar 75% wind generation mix, that point occurs when approximately 30% of heating is flexible by up to 3 hours. This could reduce the required power capacity of other flexible resources by over 20 GW.

To address sub-question 4, the degree of electric heating flexibility affects the power capacity required for flexible resources, but not the energy capacity required. Shifting electric heating demand by just one hour in either direction could bring gains of 9-19 GW of power capacity avoided. Shifting electric heating demand by more than 3 hours in either direction could reduce the required power capacity further than 30 GW, but there are diminishing marginal returns to each hour of additional flexibility. These results are based on the inflexible heating profiles from Watson et al. [111]; using a different inflexible or ideal heating profile could change the number of hours of shifting with the greatest impact.

The power capacity of flexible resources required depends on the penetration of electrification, the share of flexible devices, and the degree of flexibility. For both EVs and electric heating, increasing the electrification rate with purely inflexible assets linearly increases the power capacity required of flexible resources.

The energy capacity of flexible resources required depends on the penetration of electrification, for both EVs and for heating. Increasing the penetration of electrification and therefore the total energy demanded increases the required energy capacity of flexible resources. The amount of increase depends on the generation mix, because it depends on the temporal alignment of the additional demand with the generation.

For both EVs and electric heating, flexibility on the timescales of hours to days does not significantly affect the energy capacity needs of remaining flexibility resources.

These results hold for all fully solar and wind generation mixes and for scenarios both with and without renewable generation overcapacity.

7

Conclusion

This thesis addresses the question of *how to characterize flexibility requirements over different timescales in highly renewable power systems?* It has shown that yes, flexibility requirements over multiple timescales can be characterized and that those flexibility requirements vary with both the generation mix and the demand profile, by using the case study of Great Britain to apply the methods developed.

To mitigate the impacts of climate change, significant amounts of electricity generation will need to come from variable renewable energy sources, including solar and wind. Electrification is also a possibility for decarbonizing other sectors, including transportation and heating, provided that electricity comes from clean sources. To accommodate this shifts and still meet demand, significant amounts of flexibility will be required to store energy for later use or to shift demand to better align with the inflexible generation. There is a need to understand the capacity required of resources which can provide this flexibility.

To balance the system, some energy will need to be shifted by a few hours or even less time, while some may need to be stored for weeks, months, or even years to account for inter-annual variability in both weather and demand patterns. Because the technologies which are best suited to short-term energy shifting may not be appropriate for long-term energy shifting, there is a need to better understand the requirements for flexibility resources which operate over different timescales.

The aim in this thesis is to understand the minimum requirements for capacity of these flexibility resources under ambitious potential future scenarios. To ensure that the results characterize the requirements of the system and do not depend on assumptions about technologies or costs, there is a need to do the analysis in a way which is agnostic to the types of assets used to meet the need for flexibility.

To answer the overall research question, it is broken into the following four research sub-questions, which are addressed in each of the previous chapters. The following sections discuss the high-level insights gained from addressing each sub-question.

7.1 How to characterize flexibility requirements over different timescales

To answer this first question, this thesis makes a novel contribution of methodology to characterize the flexibility requirements over different timescales. This work develops methodology to quantify the timescales over which energy and power flexibility would be required, for a given generation mix and demand scenario.

System flexibility requirements can be characterized in terms of the total energy capacity and power capacity required for all flexibility resources in the system. To estimate the requirements for flexibility resources in the system can be estimated by first treating all resources as though they were a single storage device. The energy and power capacities of this hypothetical storage device are then the minimum total energy capacity of the aggregated flexibility assets and minimum total power capacity of the aggregated flexibility assets.

Because the types of assets which could store energy for an hour might be different from the assets which could shift energy over weeks, these aggregated requirements should be broken down into different timescales. To do this, these aggregated flexibility requirements are disaggregated based on the amount of time that energy would need to be stored or shifted for.

The novel application of three different disaggregation strategies is proposed to address this problem of separating flexibility requirements into timescale categories.

Each of these categories (for example daily, weekly, annual, and longer) could be met by a portfolio of different assets. Because this work aims to understand the temporal requirements themselves and not whether a particular set of flexible assets could meet demand under a set of specific conditions, the disaggregation strategies must be agnostic to the types of resources which would be used and not depend on technology parameters, costs, or emissions. Therefore, the timescale breakdowns and corresponding flexible resource portfolios shown are all plausible and would meet all demand, but they are not necessarily optimal from a cost or emissions perspective. However, they are still useful to understand the range of possible timescales required and, more importantly, can be used to investigate which trends hold across portfolios regardless of disaggregation strategy and therefore can inform least regrets pathways for planning and investment decisions.

Disaggregating overall storage requirements into the need for energy shifting over different timescales can be used to show how these needs could be met by portfolios with different types of storage assets. For example, if most assets available had relatively high self-discharge, one might want a strategy to maximize the amount of energy stored for the shortest amounts of time. The LIFO strategy requires mostly daily and weekly storage with high throughput, but it also requires some interseasonal and interannual energy shifting. This could align well with a portfolio of mostly batteries, in combination with hydrogen storage or flexible biogas generation with curtailment to address the long-term storage needs. However, if a different set of resources were more available or more cost effective, then one of the other strategies may be more relevant.

7.2 Flexibility requirements in fully renewable Great Britain

To answer this second question, this chapter makes novel contributions by applying the novel methodology from the previous chapter to the case study of potential future Great Britain and showing how this could inform choices about appropriate flexible resource portfolios to meet demand.

An ambitious future scenario is created as a base case. On the supply side, solar and wind power provide enough energy to meet all demand. For the base case, the solar to wind ratio is set at 1:3, with 25% of energy generated from solar and 75% from wind, based on the cost-minimizing generation mix in a one year simulation of Great Britain [89]. In addition to current electricity demand, the future demand profiles include electrifying 80% of domestic heating and 80% of private vehicles, based on the National Grid Future Energy Scenarios.

A highly renewable and electrified Great Britain will require significant amounts of flexibility to successfully meet demand and ensure a stable power system. For the base case, the total flexibility capacity required would be over 150 TWh and nearly 90 GW. This flexibility to shift energy will be needed over several timescales, from hours to potentially years.

Multiple different resource portfolios could potentially meet demand in a fully renewable and highly electrified future system. Distinct portfolio options with different capacities for daily, weekly, annual, and longer than annual resources are created using the three methods in Chapter 3. In all three cases, the energy capacity requirements for daily and weekly storage are significantly smaller (1-5 TWh) than the sizes required for interseasonal or interannual energy shifting (tens to hundreds of TWh). However, these daily and weekly resources could account for a significant portion of all energy shifting required, if they are frequently utilized.

7.3 Flexibility requirements depend on generation mix

To answer this third question, the novel methodology for differentiating flexibility requirements by timescale is applied to a wide range of possible future scenarios for GB with different generation mixes. The following subsections detail how flexibility requirements could vary with the penetration of variable renewables, with the solar to wind ratio in the generation mix, and with the amount of overcapacity of renewable generation.

7.3.1 Impact of the penetration of variable renewable energy on flexibility requirements

As expected, increasing the penetration of VRE in the generation mix increases both the energy capacity and the power capacity required for system flexibility resources. However, the nature of that increase depends on assumptions about the which generation sources provide the non-VRE share of the mix.

Results for systems where the non-VRE generation is dispatchable and flexible could inform transition pathways. They could shed light on at what point the system might start to need significant amounts of flexibility resources for which we do not currently have good options available at scale, for example interseasonal energy shifting.

Scenarios with a small about of flexible non-VRE generation could represent a systems with mostly solar and wind generation, but with some flexibility from flexible back-up generation or from interconnectors with other countries.

Systems with 20% VRE or more need the ability to shift energy by up to a day, while the need to shift energy by more than one week only affects systems with more than 50% VRE. Depending on the generation mix and the resource portfolio available, it may be possible to have a system with up to 95% VRE and 5% flexible generation without the need to shift energy for longer than one year.

7.3.2 Impact of solar wind ratio on flexibility requirements

In fully wind and solar powered systems, the required capacity of flexibility resources depends on the solar wind ratio in the generation mix.

In terms of energy requirements, systems with a mix of wind and solar power require smaller storage capacity than fully solar or fully wind powered systems. The solar wind ratio which would minimize required storage size in a fully renewable Great Britain depends on the amount of overcapacity, but appears to be between 10% and 30% solar with the rest provided by wind.

In terms of power requirements, the effect of the solar wind ratio in the generation mix is less stark but still noticeable. The power discharging requirement for aggregate flexibility resources is the maximum of the net load. Because Great Britain's peak power occurs on winter evenings when there is little to no sunlight, the peak load is also the peak net load in solar dominated mixes. Therefore, the flexibility resources would be expected to meet that peak load in solar dominated mixes. The power requirements of wind dominated mixes are slightly less, indicating that there is probably some wind power being generated at those peak net load times, but the flexibility resources would still be expected to meet the majority of power demand at those times.

For generation mixes with at least 75% solar, the need for energy shifting is almost exclusively daily or interseasonal, with very little on the order of a few days or weeks. In contrast, generation mixes with at least 75% wind have a much smoother and more even distribution of energy shifting durations.

For all solar wind ratios in fully variable renewable generation mixes and all amounts of overcapacity at least up to 2.0x, Great Britain would require between one half and one TWh of capacity for aggregated flexibility resources which could accomplish all of the daily energy shifting. This is true even for the scenarios scenarios where over half of all energy must be shifted for a day or less. Depending on how the storage assets are operated, this could account for up to 40% of all energy stored for a system with 20% overcapacity, although it would be only about 1% of the size of the overall energy storage required. This suggests that short term storage needs could be met by assets with much higher throughput and power-to-energy ratios than long-term storage needs.

The required capacity for flexibility resources to shift energy up to one year is on the order of tens of terawatt-hours for a fully renewable Great Britain, with solar dominated energy mixes requiring slightly more annual energy shifting than wind dominated mixes, and the smallest annual energy shifting capacity required for mixes between 10% and 30% solar.

7.3.3 Impact of renewables overcapacity on flexibility requirements

The need to shift energy for the longest periods of time is significantly reduced by overcapacity because more energy is generated closer to the time to when it is demanded. Related to this, the need for daily or weekly storage increases slightly as more energy is generated nearer in time to when it is demanded. These trends are consistent for all three methods used to disaggregate overall storage requirements into different timescales.

Overcapacity of 20% could potentially eliminate the need for interannual energy shifting and significantly reduce interseasonal storage sizes required, but does not reduce the need to store energy for up to a week, for all generation mixes. Given that clean long term energy storage technologies are not currently widely available and that renewable generation and short-term storage are getting cheaper while improving performance, overcapacity could enable the energy system to meet demand in fully wind and solar powered systems using only existing storage technologies.

Due to avoided storage costs, overcapacity is cost effective for all system configurations and cost assumptions. For storage to generation cost ratios of greater than 0.01 \$/Wh storage to 1 \$/W PV, up to 20% excess generation provides the greatest returns, with the marginal value of excess generation diminishing beyond this point. This analysis uses relative costs of technologies to ensure the conclusions are robust to a range of potential cost trajectories that spans four orders of magnitude. Only if the costs of storage fall precipitously would relying on storage become cost-minimizing from a system perspective. However, policy or regulatory action would be required to achieve this, because the current system provides little incentive for investors and developers to build excess renewable capacity.

7.4 Flexibility requirements depend on demand

To answer the fourth question, the novel methodology for differentiating flexibility requirements by timescale is applied to a wide range of possible future scenarios for GB with different demand profiles. In particular, this work investigates how flexibility requirements could depend on the penetration of EVs, the degree of flexibility in charging EVs, the penetration of electric heating, and the degree of flexibility in the timing of heating.

Additional demand from electrifying domestic vehicles and heating could significantly affect the required energy and power capacities of flexible resources in highly renewable power systems.

The power capacity of flexible resources required depends on the penetration of electrification, the share of flexible devices, and the degree of flexibility. For both EVs and electric heating, increasing the electrification rate with purely inflexible assets linearly increases the power capacity required of flexible resources.

The energy capacity of flexible resources required depends on the penetration of electrification, for both EVs and for heating. Increasing the penetration of electrification and therefore the total energy demanded increases the required energy capacity of flexible resources. The amount of increase depends on the generation mix, because it depends on the temporal alignment of the additional demand with the generation.

For both EVs and electric heating, flexibility on the timescales of hours to days does not significantly affect the energy capacity needs of remaining flexibility resources.

These results hold for all fully solar and wind generation mixes and for scenarios both with and without renewable generation overcapacity.

7.4.1 Impact of EVs on flexibility requirements

Additional inflexible demand from EV charging increases both the energy and power capacity required. Additional flexible demand from EV charging would increase the energy capacity required, but would not increasing the power capacity required. If most or all vehicles in GB were electrified, then increasing the share of EVs which support flexible charging linearly reduces the power capacity required.

The degree of flexibility of EV charging affects the power capacity requirements but not the energy capacity requirements. Being able to shift aggregated EV charging by up to four hours in either direction has the greatest impact on the power capacity avoided. These results are for the case where the counterfactual inflexible charging profile is based on current vehicle usage patterns and primarily used homed charging; using a different ideal charging profile could yield different results about the degree of shifting with the greatest impact. Additionally, shifting the aggregated charging profile of the EV fleet is not the same as shifting individual EV charging; an aggregated fleet could achieve shifting of four hours by shifting some individual EV charging by more than four hours.

7.4.2 Impact of electric heating on flexibility requirements

Additional inflexible demand from electric heating increases both the energy and power capacity required for flexible resources. Additional flexible demand from electric heating would increase the energy capacity by the same amount as the inflexible heating and would increase the power capacity required by less than the inflexible heating would. If 80% of heating in GB were electrified, only about 30% of heating would need to be flexible by up to 3 hours to achieve the benefits of avoided additional flexible power capacity required in system with 25% solar and 75% wind generation. This would reduce the required power capacity of other flexible resources by over 20 GW compared to the case where none of the electric heating were flexible, though it would still require more than double the power capacity compared to a situation with no electric heating.

The degree of flexibility of electric heating affects the power capacity required but not the energy capacity requirements. Shifting electric heating demand by just one hour in either direction could bring gains of 7-10 GW of power capacity avoided. Shifting electric heating demand by more than 3 hours in either direction could reduce the required power capacity further than 20 GW, but there are diminishing marginal returns to each hour of additional flexibility. These results are based on the inflexible heating profiles based on a specific mix of air source and ground source heat pumps and current building characteristics in the UK; using a different inflexible or ideal heating profile, for example with a different heat pump mix or including heat batteries, could change the number of hours of shifting with the greatest impact.

7.5 Answering the main research question

Bringing these together to answer the main research question: yes we can characterize flexibility requirements in highly renewable power systems, including the need for flexibility over different timescales. This thesis develops methods to characterize flexibility requirements over multiple timescales and then characterizes the requirements for potential future scenarios for Great Britain.

The need for flexibility can be characterized by the minimum total capacity all flexible assets which could meet demand. This resource capacity can be measured in terms of the energy capacity and the power capacity required. The requirements for flexibility over different timescales can be found by disaggregating the overall need for flexibility into particular timescales of interest. One contribution of this thesis is the novel application of three methods which enable these flexibility requirements at multiple timescales to be assessed for particular future scenarios. Comparing the results from these independent strategies can yield insight into which results and trends hold across all strategies and are therefore more likely to offer insight into least regrets planning and investment decisions.

Using these methods on the case study of Great Britain shows that highly renewable power systems will need a high degree of flexibility, but the amount of flexible resource capacity and the timescales over which it must operate depend on both the generation mix and the demand profiles. This flexibility will be required over all timescales, from (less than) hourly to interseasonal or longer. The generation mix for GB which minimizes the required flexibility capacity is about 25% solar and 75% wind, though the optimal mix could be shifted toward higher shares of wind if significant shares of heating are electrified or if more offshore wind is developed. Overcapacity of renewable generation can provide significant value in terms of avoided storage capacity and avoided costs, in particular displacing the need for the longest duration storage, though there are diminishing returns to marginal generation capacity beyond 120% of demand. Electrification of vehicles will increase flexibility requirements, but making those EVs themselves flexible can offset the need for additional power capacity of flexible resources. Electrification of heating will have a much larger impact on flexibility requirements than EVs, and making the heating flexible can partially offset the need for additional power capacity of flexible resources.

In all cases, the capacity required to shift energy by up to a day was on the order of 1 TWh or less, although this could account for over half of all energy shifted, depending on the operation of the flexible asset portfolio. The required capacity to shift energy by more than one year could potentially be avoided overcapacity of renewables, dispatchable generation, interconnectors. However, it is likely that some form of long-duration or interseasonal storage will be required to meet demand in a more heavily renewable and electrified future.

Future work could extend this analysis and investigate the robustness to particular assumptions, in particular around spatial considerations, efficiency assumptions, and the case study choices. Including a spatial dimension, to investigate the impact of location of generation and demand and of network constraints, would add great insight and is already underway by another doctoral student in the research group. Although these results were intentionally technology agnostic and used perfect efficiency to yield a lower boundary estimate of resource capacity required, more thoroughly investigating the effects of storage efficiency on required resource capacity would be beneficial for future system planning. Extending these methods to other locations could not only yield insights into future power system planning for those locations, but enable greater understanding of how generation and demand patterns could influence future system requirements.

The thesis has shown how these flexibility requirements depend on the generation mix and demand patterns and has yielded insights which could inform investment and planning decisions for the energy transition.

Appendices

A
Appendix

A.1 Time resolution

To understand the effects of the time resolution of the data on the results, this section briefly investigates results using larger temporal resolutions than hourly. The demand and supply data used for the base case in Chapter 4 were resampled at daily, monthly, and annual frequencies and then used to calculated the overall flexibility requirements. Figure A.1 shows the results for this base case and Table A.1 summarizes the minimum required capacities.

Table A.1: Comparison of capacity requirements using data at different temporal resolutions

Resolution	Storage (TWh)	Storage (GW)
Hourly	154.6	89.4
Daily	153.2	72.5
Monthly	148.1	40.5
Yearly	85.7	9.2

Using these different temporal resolutions could yield insight into the underlying flexibility requirements at different timescales. Using hourly data implicitly assumes that sub-hourly energy shifting needs have already been met, so results how the need to shift energy by one hour or longer. . Similarly, using daily data assumes that energy shifting by a day or less has been accounted for, so results should yield

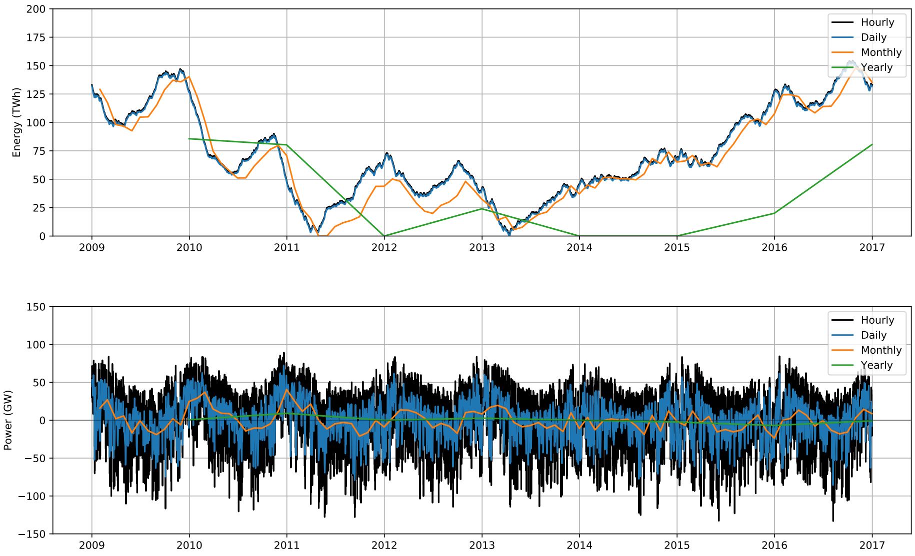


Figure A.1: Overall flexibility requirements results depend on the temporal resolution of data used.

the need for shifting energy by a day or longer. Using monthly data shows the need shift energy by one month or longer, and using yearly data shows there is definitely some need for interannual energy shifting.

The capacity requirements in Table A.1 are a useful first pass and can help sense-check the results. However, because the data resampling uses mean values, this process potentially smoothes over some of the extremes.

It is quite clear that the temporal resolution of data matters. Finer time resolutions could improve the results by accounting for energy shifting within the hour, but this was not possible for this thesis due to data constraints.

A.2 Extended demand profiles

To test the need for interannual flexibility and account for weather events that might happen even less frequently, it is valuable the use the over three decades of historical weather data available. While this cannot account for events that happen even less frequently, it can potentially provide more insight than the eight years used in most of the thesis; however, there is then a need for credible demand profiles over that four decade time horizon.

As described in Chapter 3, the decision to use only the overlapping years of historical data was deemed most credible and therefore was used for the majority of the analysis in the main body chapters in the thesis. However, longer term multi-decade simulations were carried out to test the effects of this interannual variability in the weather and to understand the effects of the simulation time horizon on the results (see Section A.3).

Several options were considered, including repeating all ten years of available demand data; repeating all ten years but following the decreasing trend of mean power; choosing a single year to repeat; repeating a subset of the most years to repeat; and selecting individual demand years to match with individual weather years based on external criteria such as temperature.

For these longer term analyses, the most recent years 2016-2019 are repeated and appended to create longer potential future demand profiles, while the wind and solar data from 1980 to 2008 are appended to approximate future weather patterns. Aligning years based on other criteria, such matching weather and demand profiles from relatively warm or relatively cold years would be another potential option, though would require assumptions about how often each warm or cold year comes in future and in which order and might require smoothing between the different year profiles. Using the most recent four years of demand data ensured that recent trends in electricity usage were preserved, but there was still some variability between years. Appending the generation data preserved the order in which the warm and cold years historically occurred and was therefore deemed a more credible potential long term profile.

A.3 Simulation time horizon

As explained in Chapter 4, the results presented here use simulations with a time horizon of eight years due to data constraints. However, it is worth understanding how this choice may affect the findings.

The number of years in the simulation affects estimates of required storage and generation capacity [124, 125]. Multiyear simulation enables investigation of potential needs to shift energy between seasons and years. It also means the study can account for variability of weather and demand patterns.

The results here can help determine how many years of data are required to ensure the results are robust, while also reducing the computational load. It can also illuminate potential uncertainty in results from studies which have shorter simulation durations.

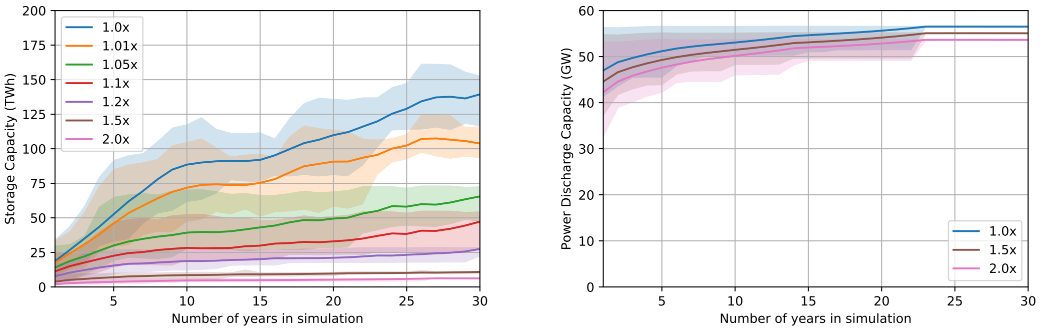


Figure A.2: Effect of simulation length on storage requirements for 25% solar, 75% wind case. Shaded regions show maximum and minimum capacity requirements. Note for longer simulations, the smaller shaded area does not necessarily imply greater certainty, just fewer data points.

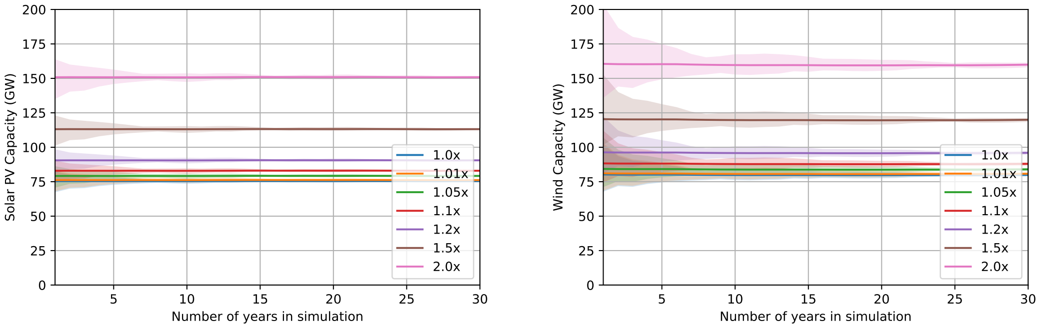


Figure A.3: Effect of simulation length on installed generation capacity requirements for 25% solar, 75% wind case. Shaded regions show maximum and minimum capacity requirements. Note for longer simulations, the smaller shaded area does not necessarily imply greater certainty, just fewer data points.

Examples of how the storage capacity results vary based on the simulation length are shown in Figure A.2, for the 25% wind, 75% solar case. The shaded areas represent the maximum and minimum capacities required; note that for longer simulations, the smaller shaded area does not necessarily imply greater certainty, just fewer data points. For example, if one divided analysis into calendar years, there are 32 stretches of five consecutive years to test, but only seven of 30 consecutive years. Because the power capacity needed is set by the maximum net load, power capacity requirements eventually converge to the value from the single year with the greatest net load, as that year is eventually included in all of the longer simulations. For clarity, power capacity requirements in Figure A.2 are shown only for the 1.0x, 1.5, and 2.0x cases, but the others follow the same pattern.

The single year simulation for Great Britain, at the left of Figure A.2 where number of years in simulation is one, agrees well with existing literature [89]. One reason the overall storage requirements reported here are much higher may be because this analysis accounts for interannual variation in renewable generation and demand. More importantly, it suggests there is a substantial need for interannual energy shifting, whether or not this mismatch is met by storage or by flexible dispatchable generation and further curtailment.

Figure A.2 shows the storage energy capacity required increases with the number of years in the simulation. Given the plateaus reached in the storage power capacity in Figure A.2 and generation capacity in Figure A.3, this may seem surprising and may be due to several factors. The 1.0x case is a useful conceptual baseline, with exactly enough energy generated as demanded. However, for some combinations of demand and renewable generation, it could require that some energy is generated several years before it is demanded and must be stored in between, increasing the storage size needed. For simulations with 20% overcapacity (1.2x) or more, the maximum and minimum values converge and begin to plateau after 10 to 15 years are included. Alternatively, it is possible that even three decades is not enough to account for the variability in weather and demand.

The plateaus reached in Figure A.3 clearly show that the average generation capacity required for 37 years can already be well approximated by simulations over one or two decades, but that simulations over five years or less may not yield accurate results.

While using over three decades of data cannot account for extremes which occur more infrequently, the analysis here should cover most of the typical interannual variation. Often, including here, the length of the simulation is limited by the availability of data or computational power required for high temporal resolution over longer time horizons. Future research could investigate the effects of potential changes to weather and demand profiles due to climate change, technology development, and social change.

A.4 Validation of multi-annual Great Britain results

The overall storage requirements model presented in Chapter 3 is validated against a storage reliability model [23] for Great Britain for multiyear simulations.

As shown in Table A.2, both approaches yield very similar minimum storage sizes required for 100% reliability for Great Britain. Table 3.2 shows that this model yields the same results as to the published values [23] when applied to the continental United States. The agreement is not surprising because the storage energy capacity required calculated using this overall storage requirements model is theoretically equivalent to the minimum size for 100% reliability.

Table A.2: Comparison of storage size required for GB calculated using the overall storage model presented here and [23].

Solar / wind ratio	Overcapacity	Storage (TWh) [23]	Storage (TWh) This model
25% / 75%	1.0x	250.488	250.348
	1.2x	50.098	49.842
	1.5x	17.285	17.036
	2.0x	6.445	6.445
75% / 25%	1.0x	249.512	249.596
	1.2	71.191	71.107
	1.5x	51.855	51.626
	2.0x	31.641	31.446

Results are also compared to a single year simulation which uses the same case of Great Britain [89]. For Great Britain specifically, one study based on a single year simulation estimates that 14.93 TWh of storage is needed for the 25% solar, 75% wind case with no overcapacity (1.0x), while 7.93 TWh would be needed for 21% solar, 79% wind with 5% overcapacity (1.05x) [89]. These size estimates are much lower than results presented in Chapter 5, likely because they do not account for interannual variation in demand or renewable supply, which leads to the need for interseasonal energy shifting. Running the model presented here for every combination of one-year demand and generation profiles available yields results between 8 TWh and 35 TWh in the 1.0x case and between 4 TWh and 28 TWh in the 1.05x case, which is on the same order of magnitude as in and shows similar tradeoffs between storage and overcapacity.

The overall storage sizes presented in here are greater than most values in Blanco et al.'s review, which shows reported storage sizes up to 15% of annual electric energy demand with the vast majority below 6% of annual demand for 100% renewable scenarios [103]. The discrepancy may be due to several reasons. First, some of the studies included in the review use dispatchable renewable hydropower or biomass, which would provide some flexibility and reduce the need for dispatchable power from storage. Second, this review includes studies from many different regions, where electricity demand may be better temporally aligned with renewable generation. Third, most of the included studies focus on the power sector, which the authors point out are more likely to focus on short term simulations rather than taking a multi-year energy perspective, and therefore may miss interseasonal energy shifting needs.

A.5 Effect of overall energy shifting efficiency on temporal flexibility requirements

By assuming completely efficient energy shifting, estimates for size are the absolute minimum required. With inefficient energy shifting, both installed generation capacity and flexible resource capacity would need to be larger to make up for losses.

The that the size of aggregate energy shifting resources required appears to increase with more efficient energy shifting in Figure A.5 is potentially unexpected. Each scenario has exactly enough energy to meet demand, accounting for the

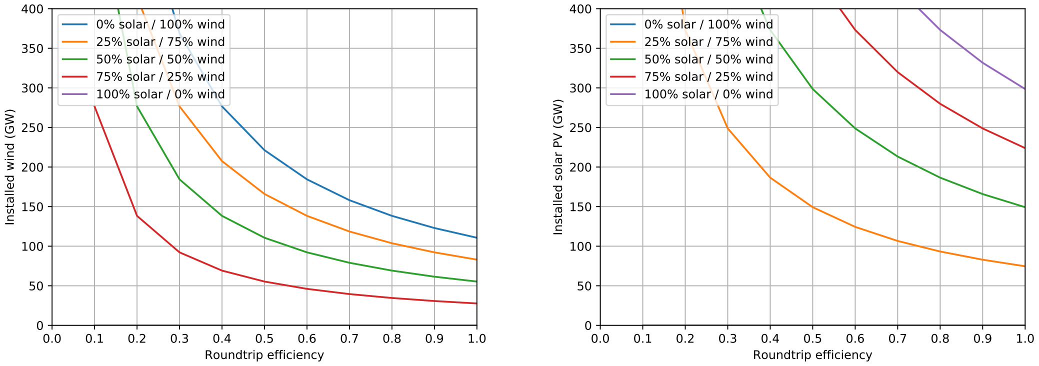


Figure A.4: Installed generation capacity for different solar wind ratios in the generation mix for different levels of energy shifting efficiency.

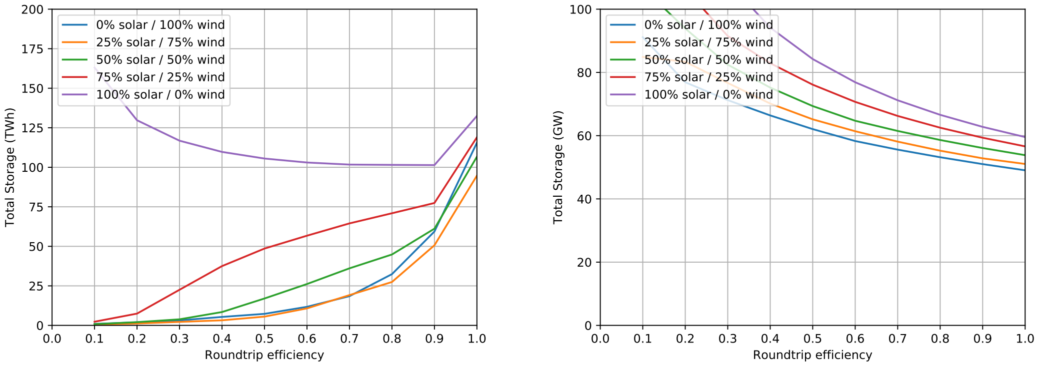


Figure A.5: Overall storage capacity required for different solar wind ratios in the generation mix for different levels of energy shifting efficiency.

inefficiencies, which means additional energy generation is required to meet demand in systems with less efficient energy shifting. Systems with very low average energy shifting efficiency therefore have significantly more additional installed generation capacity, shown in Figure A.4, which means more generation is temporally aligned with demand and less energy shifting may be required.

Due to night-time demand, only the fully solar powered system cannot rely on the additional generation to be aligned with demand at all times. This case shows a more expected relationship for low efficiencies, where increasing efficiency decreases the size required. For efficiencies closer to 100%, the effects of the additional required generation aligning better with demand begin to outweigh the effects of higher efficiency in terms of storage capacity avoided.

In terms of power capacity, the reduction in power capacity required with increasing efficiency is expected. Although the power requirements for each solar to wind ratio shown are slightly different, with solar dominated mixes requiring slightly greater power capacity as discussed in Section 5.2, the roundtrip energy shifting efficiency appears to affect systems with all generation mixes in the same way.

A.6 Heat flexibility for up to 48 hours

Some simulations were run testing the effects of the flexibility of electric heat demand by more than 12 hours; however, this was not explored further as it was not deemed a realistic possibility given both UK housing stock and social practices.

Figure A.6 shows how flexibility of heating by up to 48 hours in either direction could affect the need for flexibility, for a single year simulation. In these figures, all heating is electrified and the different curves refer to the share of that heating which is flexible.

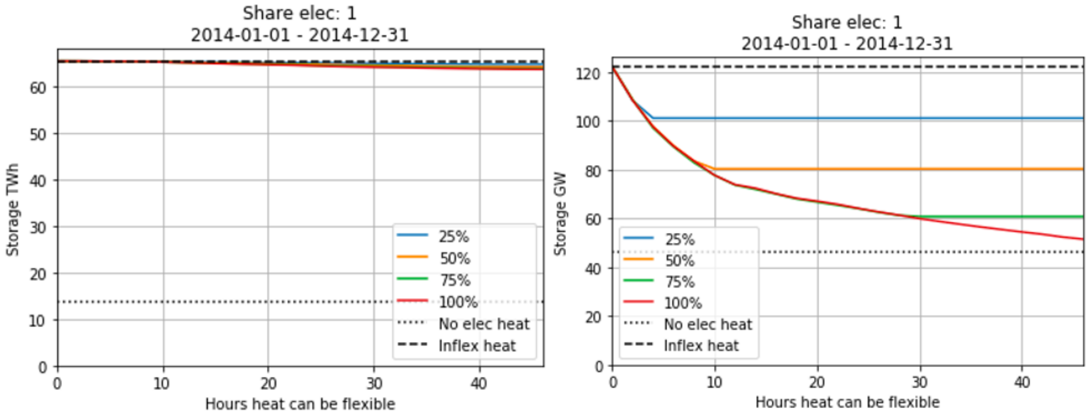


Figure A.6: Overall storage capacity required for different solar wind ratios in the generation mix for different levels of energy shifting efficiency.

Note that for the case where all heating is flexible, flexibility of up to 48 hours nearly eliminates the need for additional power capacity. However, one would not necessarily expect this to hold in reality, as it does not account for interannual variation in weather or demand.

A.7 Climate change effects on heating and cooling demand

We explored the possibility of investigating the effects of climate change on cooling and heating demand. However, due to data constraints and the timing of model runs, this was not able to be included in the main analysis. Preliminary work calculating thermal demand in terms of heating degree days (HDD) and cooling degree days (CDD) was completed with the data which had been returned by end of 2021 and is included in this section.

A high spatio-temporal resolution model Met Office Hadley Centre global atmospheric model (HadAM4) was run in collaboration with the Oxford eResearch Centre. Note that the model is still in development and may still require bias correction, so the figures an results below should be considered indicative only at this stage. The temporal resolution was 6 hourly. The spatial resolution is 0.55 degrees by 0.833 degrees, which corresponds to about 60 square kilometers though this varies with position on the globe.

Three different scenarios were set up: recent historical, 1.5 C, and 2 C. The recent historical scenario ran the model for 2006 to 2015, which corresponds to about a 1 degree C increase in global temperatures. These results could then be compared with historical data for calibration. The model was then run for scenarios at global average temperature increases of 1.5 degrees C and 2 degrees C.

Each scenario includes over 2000 runs to yield a range of possible future. At the time of this work, only 400 were completed for the scenario with the fewest results returned; therefore 400 runs were selected randomly from the other scenarios to ensure the figures were comparable.

Figures A.7 and A.8 shows median cooling and heating degree days for the globe for two seasons for the three scenarios. These maps show where the particular hot spots and cold spots will be globally. To understand what this will mean for heating and cooling demand, it will be necessary to weight these by population.

Figures A.9 and A.10 show the change in CDDs and HDDs respectively between each of the three scenarios. These maps show the areas where the changes will be greatest, which may mean the areas which need to adapt the most. They also clearly show that getting to 2 C will increase cooling demand significantly more than just 1.5 C.

HDDs and CDDs are reported as seasonal totals, as only two seasons had returned sufficient data at the time of analysis. A base temperature of 18 degrees C was used for both HDD and CDD calculations.

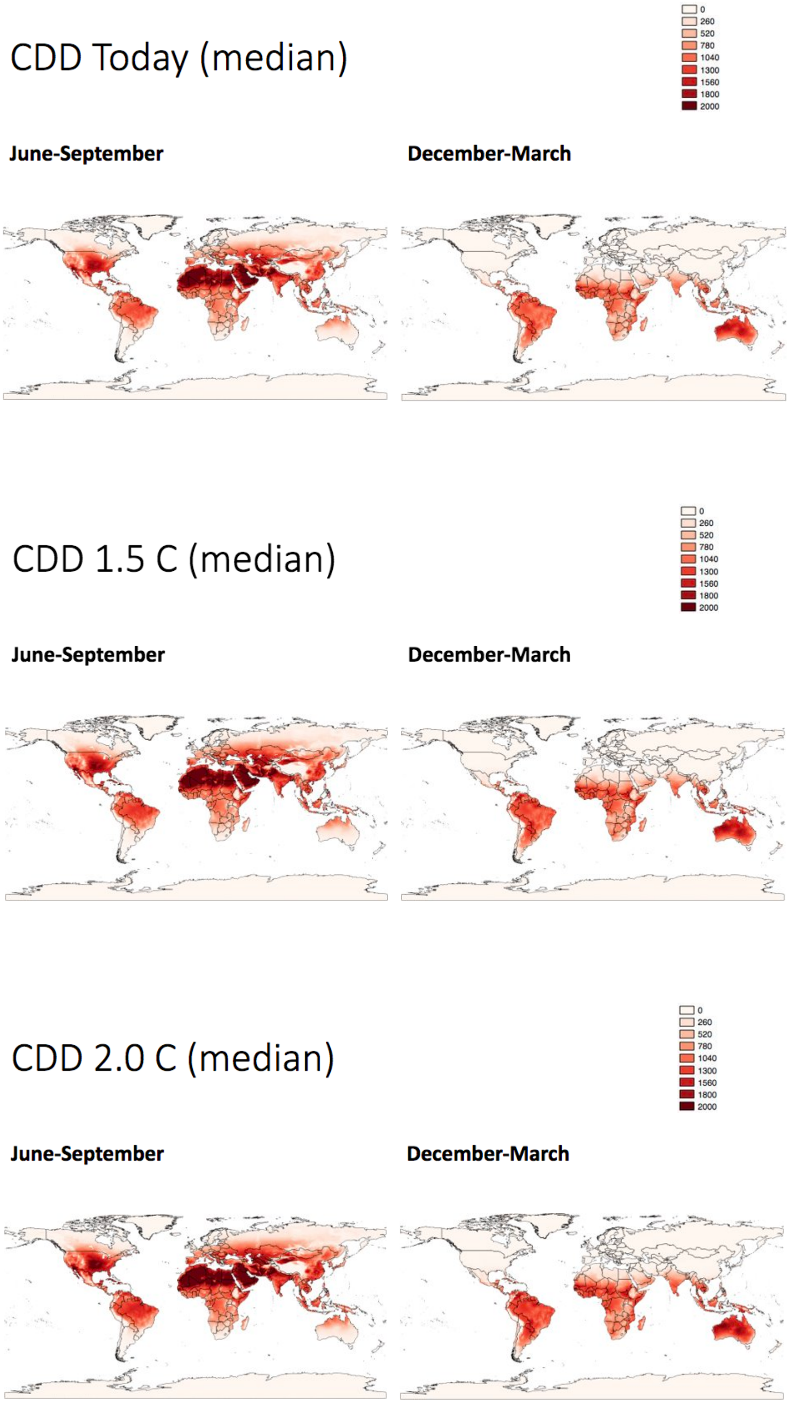


Figure A.7: Global cooling degree days.

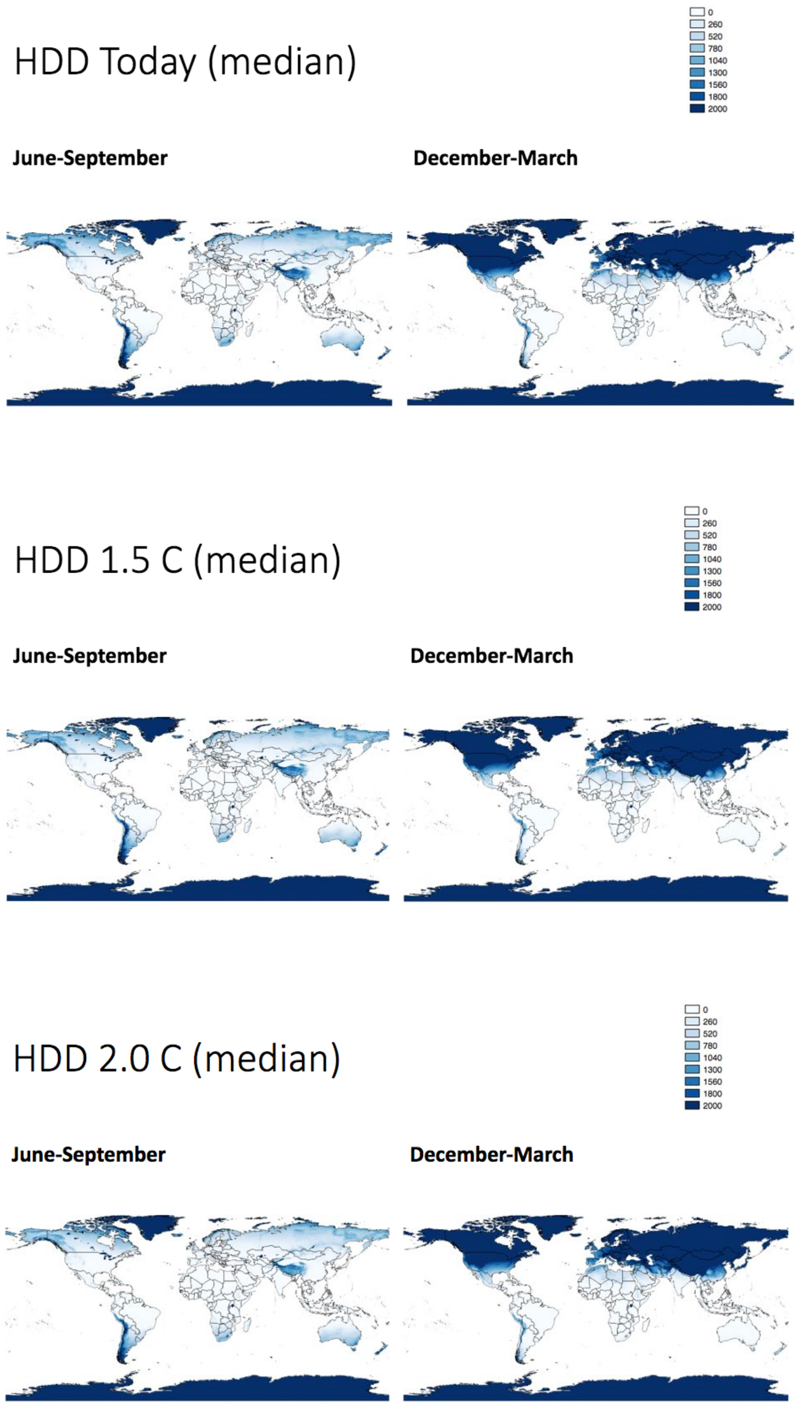
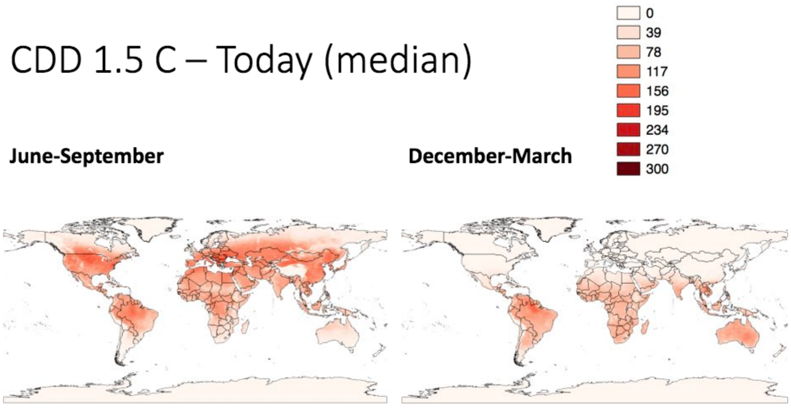
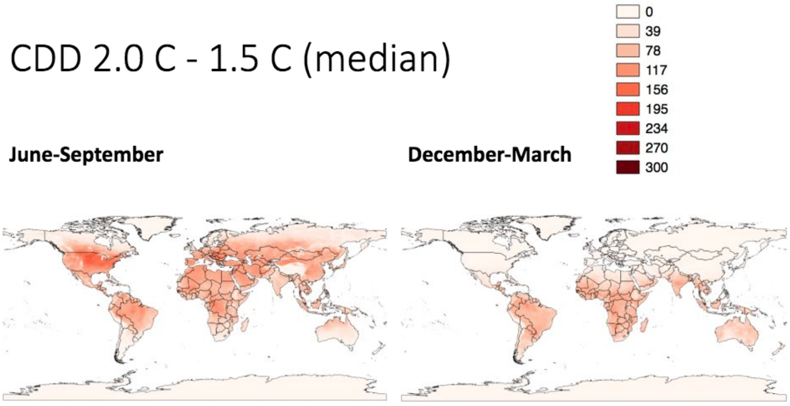


Figure A.8: Global heating degree days.





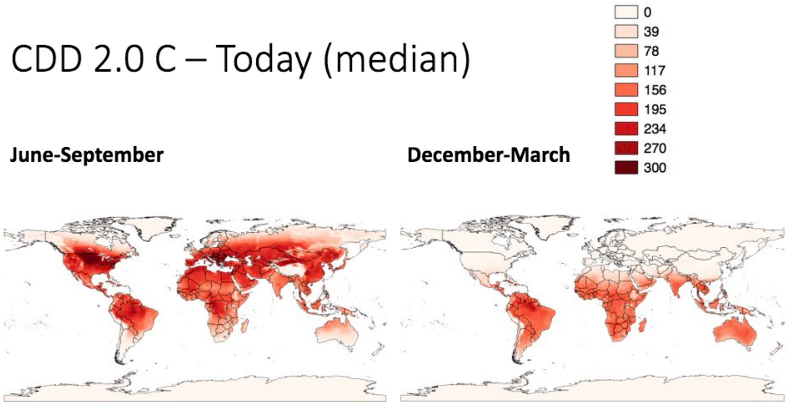


Figure A.9: Change in global cooling degree days.

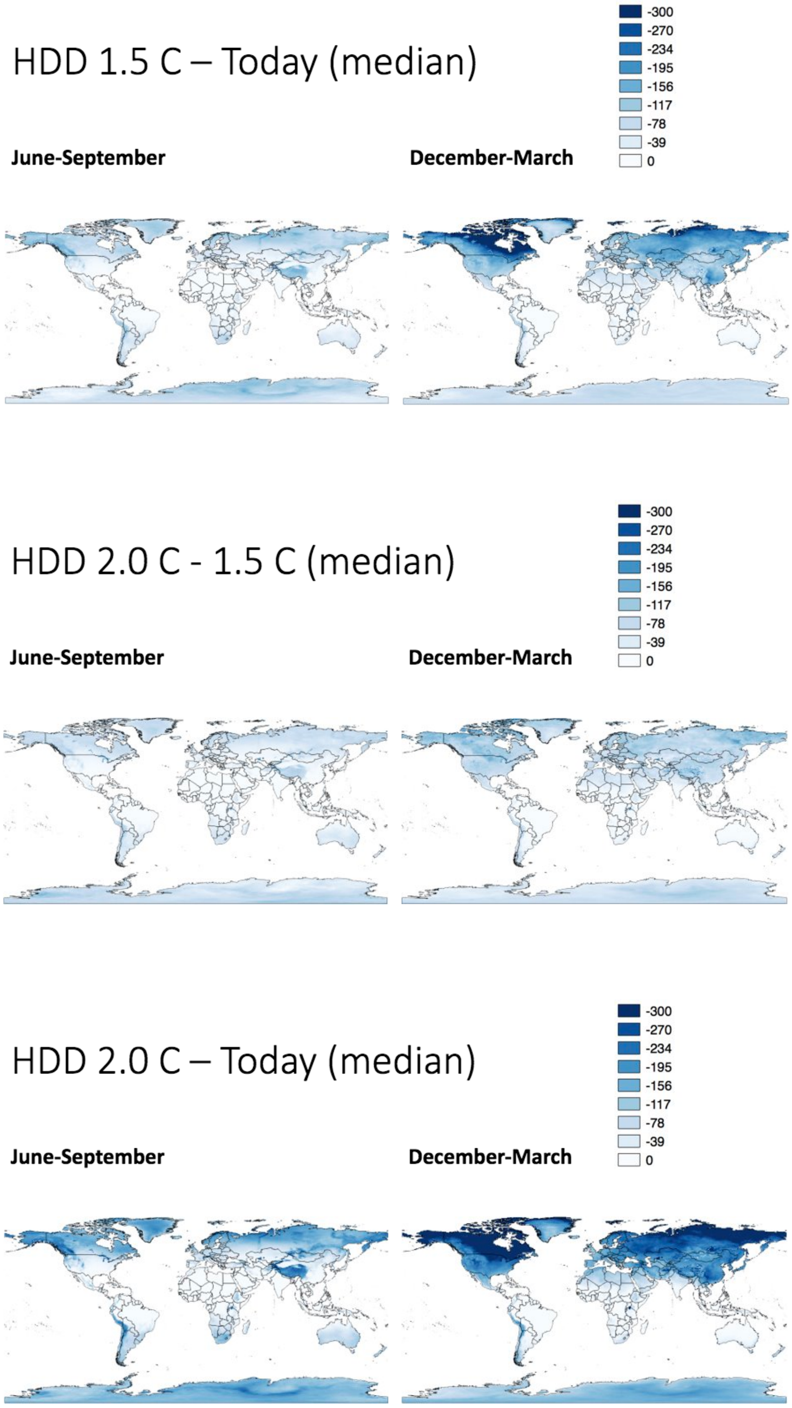


Figure A.10: Change in global heating degree days.

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