Technological University Dublin
ARROW@TU Dublin

Articles

2023-09-23

Sustainability Matchmaking: Exploration into using excess renewable energy to deliver ‘free’ energy to fuel poor homes – a preliminary case study in Ireland

Ciara Ahern
Technological University Dublin, ciara.ahern@tudublin.ie

Ronan Oliver
Technological University Dublin, ronan.oliver@tudublin.ie

Follow this and additional works at: https://arrow.tudublin.ie/creaart

Part of the Energy Systems Commons

Recommended Citation

Ahern, Ciara and Oliver, Ronán, Sustainability Matchmaking: Exploration into Using Excess Renewable Energy to Deliver ‘Free’ Energy to Fuel Poor Homes – a Preliminary Case Study in Ireland. Available at SSRN: https://ssrn.com/abstract=4566515 or http://dx.doi.org/10.2139/ssrn.4566515

This Article is brought to you for free and open access by ARROW@TU Dublin. It has been accepted for inclusion in Articles by an authorized administrator of ARROW@TU Dublin. For more information, please contact arrow.admin@tudublin.ie, aisling.coyne@tudublin.ie, gerard.connolly@tudublin.ie, vera.kilshaw@tudublin.ie.

This work is licensed under a Creative Commons Attribution-NonCommercial-Share Alike 4.0 International License.

Sustainability Matchmaking: Exploration into using excess renewable energy to deliver 'free' energy to fuel poor homes – a preliminary case study in Ireland

Ciara Ahern[a,b] ,Ronan Oliver[a]

[a] Dublin Energy Lab, Technological University Dublin, Ireland

[b] MaREI, Cork, Ireland

Abstract

The aggregated fuel cost of domestic hot water (DHW) generation in Ireland, in 2022, was €529M with associated emissions/load of 1.3MtCO_2/289GWh. The shadow price of carbon monetises the negative impact of emissions, rising with time; DHW generation has an associated shadow carbon cost of €13M in 2022, rising to €42M in 2030 and €335M in 2050.

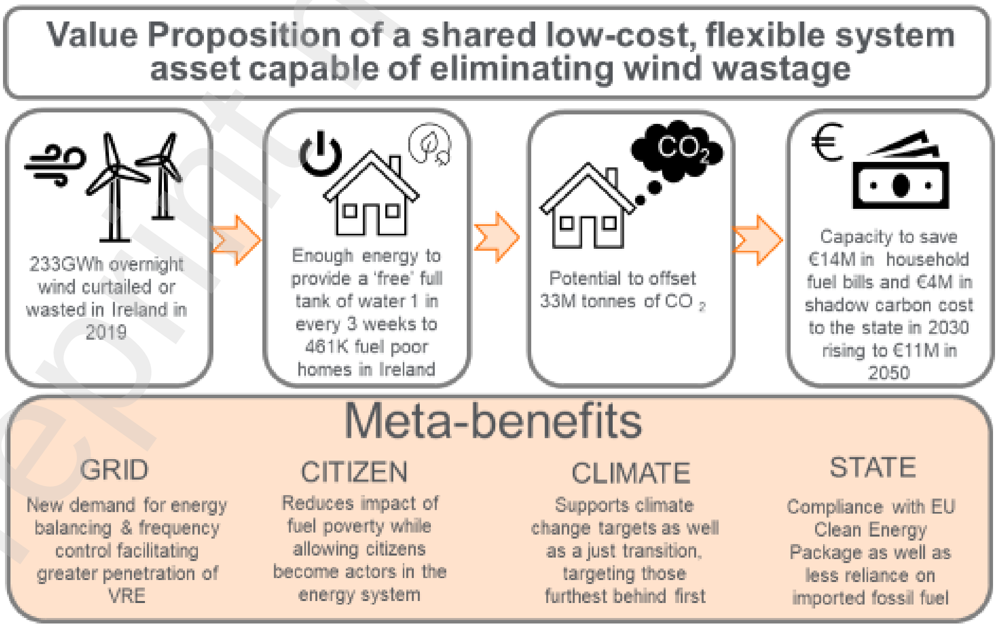
In 2020, c12%/€441M of wind was curtailed or wasted as *inter alia*, there was no demand at times of high wind. Meanwhile, a 'silent crisis' is occurring in Ireland wherein one-in-two dwellings were considered in fuel poverty in 2022. Households in fuel poverty are known to limit DHW generation, impacting hygiene and well-being.

As most Irish households have an electrical immersion *already* installed in DHW tanks, this research develops a preliminary (first round) wind allocation model to assess the potentials and economics of redeploying excess wind to heat DHW and, in the interest of a just-transition, focuses on households at risk of fuel poverty.

It is found that fuel-poor households in Ireland could be theoretically provided with a 'free' *full* tank of hot water, once in every 3 weeks, redeploying 89% of overnight curtailed wind energy in 2019, realising a potential carbon cost saving to the Irish state of c€4M in 2030, rising to c€11M in 2050 along with a better quality of life for fuel-poor citizens.

This research concludes this massive, readily deployable, shared, citizen-owned dispatch-down resource should be utilised and further research into redeployment of dispatch-down as a service is merited.

Graphical Abstract



Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

Highlights

1. First energy deployment model of excess wind developed for Ireland.
2. Focuses on a readily deployable e-HVAC technology, but findings are generalisable.
3. In the interest of a just-transition, first EWH study to focus on fuel-poor households.
4. Informs demand side management and response strategies for the residential sector.
5. Illustrates how advantages can be taken of dispatch-down to obtain more services.

Keywords

Demand side management, e-HVAC, dispatch down, curtailment, electrical water heating, fuel poverty.

Abbreviations

BRE	British Research Establishment
DHW	Domestic Hot Water
DSM	Demand Side Management
DSR	Demand Side Response
EDF	Électricité de France
e-HVAC	electrical Heating Ventilation and Air-Conditioning
EWH	Electrical Water Heating
HVDC	Hig-voltage Direct Current
SETS	Smart Electric Thermal Storage
SNSP	System Non-Synchronous Penetration
TSO	Transmission Service Operator
VRE	Variable Renewable Energy

1 Introduction

Increased penetration of wind and solar energy into power systems is being sought to offset fossil fuels and decarbonise electricity generation [1]. Driven by climate change policy and incentives as well as declining technology costs, penetration of renewable energy generation, particularly wind and solar energy, has increased substantially [1, 2] and is set to continue [3] with;

- the share of renewable energy in the energy mix of the European Union (EU) targeted to double from 17.5% in 2017 to 34% in 2030 [3], while
- the United States is targeting a 50% to 52% reduction in greenhouse gas (GHG) emissions from 2005 levels by 2030 [4], and
- China has pledged that 25% of its primary energy will be derived from non-fossil fuels by 2030 [5].

In line with these ambitious targets, global electricity generation capacity of wind farms has multiplied over threefold from 200GW in 2010 to 650GW in 2019, providing almost six per cent (5.9%) of the world's electricity demand in 2019 [6]. Countries wherein wind met a significant amount of the national electricity demand in 2019 are Denmark (47.2%), followed by Ireland (30.7%), Portugal (26.3%), Germany (21.2%) and Spain (20.8%) [6]**.**

1.1 Dispatch-down

Electrical power generation is classified as being either synchronous or non-synchronous [7]. Synchronous generation refers to traditional power generation relating to hydro, gas, coal, oil and pumped storage as well as biomass that power large rotating electrical generators spinning together in synchronism (50Hz) whereas non-synchronous generation refers to electricity produced from non-traditional sources such as renewable energy sources, High-Voltage Direct Current (HVDC)

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

interconnector imports and battery storage [7] . Increases in variable unpredictable [7] non-synchronous renewable energy such as wind and solar are resulting in electrical power systems encountering transmission and/or operational constraints imposed to maintain system stability, forcing system operators to sometimes accept less wind or solar energy than is potentially available [8]. This research refers to this phenomenon as 'dispatch-down'; wherein renewable energy farms are instructed to reduce the amount of power they can generate to ensure that there is sufficient dispatchable synchronous generation on the system to *inter alia* maintain security of supply and system stability [8]. System Non-Synchronous Penetration (SNSP) is a real-time measure of the percentage of generation that comes from non-synchronous sources relative to the system demand given by Eqn. 1:

$$SNSP = \frac{Non - synchronous\ power}{Synchronous\ and\ non - synchronous\ on\ the\ system} = \frac{Wind + Solar + HVDC}{Electricity\ Demand + Exports} \qquad \text{Eqn. 1}$$

To support frequency and voltage control while accounting for operational constraints, prevailing plant portfolios and system capability, Transmission System Operators (TSOs) limit SNSP [7], also referred to as Variable Renewable Energy (VRE) limit [9]. There are 3 types of dispatch down [7] arising from:

a) *Curtailment* – when wind power production exceeds SNSP limit, addressed by dispatching-down wind generators across the entire national grid.
b) *Constraint* – when line or cable capacity cannot transmit the electricity produced to serve demand because there is [10]:
    i) more wind generation than the localised carrying capacity of the network, or
    ii) an outage for maintenance, upgrade works or faults, or
c) *Energy balancing* – when generation exceeds demand.

In most countries, the incorporation of increasing amounts of renewable energy has become an energy policy priority resulting in TSOs working to increase VRE penetration or SNSP limits [9]. By way of example, the SNSP limit in Ireland in 2020, was 65%, rising to 75% in 2021 with strategies in place to meet a 95% target by 2030 [7]. When wind farms are dispatched down, they are typically replaced by fossil fuel generators and consequently CO_2 emissions rise. Thus, to achieve climate change targets dispatch down needs to be reduced while the use of renewable electricity on grid needs to be maximised [7]. Ireland has some of the best renewable energy resources on the planet, being second only to Denmark in the share of renewables in the electricity generation mix, however, as an island country, it has a relatively isolated electrical system and so experiences some of the highest levels of dispatch down in Europe [6, 11], it also means that Ireland needs to realise greater mechanisms for flexibility capacity [12], particularly as dispatch-down due to energy balancing (type c) is forecasted to increase significantly in line with greater penetration of wind energy targeted by ambitious climate policy [7, 13].

The literature has traditionally viewed dispatch-down as a "bad" thing , in terms of wasted energy [9, 14] or a "major problem" limiting penetration of VRE [15], however, in the last two years, studies have begun to emerge as to how advantages can be taken of dispatch-down to obtain more electrical [16-19], financial [20] and social [17] services as well as supporting an increase in VRE/SNSP limits through flexibility provision [21]. Dispatch-down is also an energy resource that has significant monetary value; based on average yearly electricity retail price of electricity to the market/householder, the total value of dispatch down in Ireland over the last 5 years is estimated at €1.11 billion, shown in Table 1 to range from €85M in 2017 to €441M in 2020.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

Table 1 Average market retail value of dispatch down electricity from 2017 to 2021

	2017	2018	2019	2020	2021
GWh^	386	707	1,008	1,909	752
€/kWh*	0.22053	0.22607	0.23213	0.2312	0.2456
€ Total M	€ 85	€ 160	€ 234	€ 441	€ 185

^www.eirgridgroup.com/site-files/library/EirGrid/year-Qtr4-Wind-Diparch-Down-Report.pdf

*https://www.seai.ie/data-and-insights/seai-statistics/key-statistics/prices/

1.2 Demand Side Management

Reducing dispatch down is viewed a complex challenge requiring deployment of new technologies that have not been a significant feature of electricity systems to date such as battery and electro-thermal storage as well as demand side management/response (DSM/DSR) to provide system stability and flexibility [7, 22]. DSM comprises a set of load management strategies, incorporating planning, integration, and monitoring of pre-assigned routine activities based on the consumer's usage pattern [23] whereas DSR can be defined [24] as "changes in electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments". The goal of a DSM/DSR system is to efficiently use the available energy without the necessity of installing new transmission infrastructure. Indeed Article 32 of the EU 2019 Clean Energy Package [25] sets a new requirement on the use of flexibility in distribution networks and its procurement, requiring TSOs to consider flexibility in grid planning as an alternative to system expansion [19]. As the residential sector accounts for a significant part of the overall load (25% in Ireland [22]), it is acknowledged that residential sector plays a vital role in terms of its impact on overall power balance, stability, and efficient power management [26] and thus Article 32 further requires the effective and non-discriminatory participation of *all* market participants, including allowing market access for residential consumers. Notwithstanding, only a fraction of the demand side flexibility potential in the residential sector is being utilised [27]. Residential customers in Ireland can only participate in DSM/DSR through tariff-based schemes where they are encouraged to move their usage to cheaper off-peak night-time hours. To comply with Article 32, it is necessary to allow market access to householders.

1.3 Irish Context

There have been two large DSM studies carried under Horizon 2020 with the Irish TSO as participant, the first, entitled RealValue [28] ran from 2015 to 2018, deployed Smart Electric Thermal Storage (SETS) in 1250 homes in Germany, Latvia and Ireland demonstrating scalability through modelling and virtual simulation [29, 30], finding that SETS can meet householders' space and water heating needs in a low-cost and energy-efficient manner, whilst enabling the electricity industry to exploit its energy storage capacity. RealValue connected residential SETS to a cloud aggregation platform allowing the storage heaters to take on charge based on grid constraints and market price signals, seeing "SETS as a means for an ordinary person to participate in the evolving energy system." While understanding that "Not everybody is going to have the money to invest in a Tesla battery, an electric car, a wind turbine, or PV for their roof. But lots of people have storage heaters heating their buildings, consuming a large amount of energy" and seeing "SETS as being a means for these people to be active and important cogs in the future EU energy system" [28].

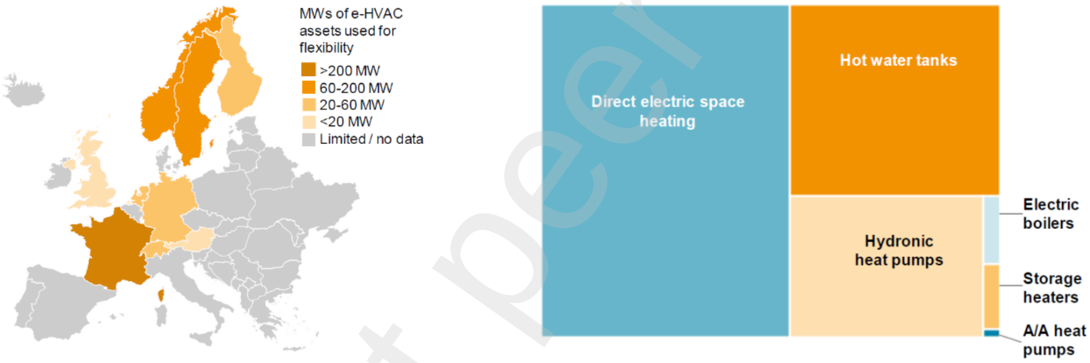
Due to a historically high price of electricity in Ireland, compared to other European countries, most homes In Ireland heat their homes and hot water through a fossil fuelled hydronic radiator systems and thus do not have electric storage heating installed (smart of otherwise) [31]. Most Irish homes (77%) do however also have a secondary electric hot water immersion fitted to domestic hot water tanks which can act as a backup or as an alternative to the boiler as required.

The second DSR/DSM study, entitled EU-SysFlex project [22], carried out between 2018 and 2020 trialled *inter alia* 'Residential Service Provision' through the Power Off and Save project [22, 32], that engaged over 1,400 households over a 2-year period with participants asked to reduce their electricity

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

consumption at peak times through both manual and automated means. The trial provided an early demonstration of what can be achieved by harnessing multiple domestic electrical loads, and while many such loads will be increasingly available (e.g. EVs, storage heaters, heat pumps), the Power Off and Save trial showed that switching electrical water heating through the 3kW immersion heater is a viable and cost-effective way to control domestic electrical load [32]. Indeed, electric heating (space heating and hot water) or electric -Heating Ventilation and Air Conditioning (e-HVAC) promises to play a key role in providing much needed demand side flexibility in the energy system, particularly the residential energy system [27]. Fig. 1a illustrates how Ireland is lagging France, The Nordics, Germany, Netherlands, Austria, Switzerland, and the UK in adoption of e-HVAC assets providing system flexibility, while Fig. 1b, illustrates that how hot water tanks make up around a quarter of the capacity used in residential demand side flexibility applications [27]. Certainly, hot water tanks are being recognised increasingly as being potentially the most flexible e-HVAC retrofit solution as the addition of smart controls indicating levels of useful hot water available at any time allows tanks to effectively perform like batteries (see Fig. 2) [33-40]. Moreover, via smart controls providing information to the customer, the customer can, in principle, be in more control themselves, or via data and analytics that work on their behalf, over how much hot water they need at particular times [41].



a) **MWs of HVAC assets used for flexibility across Europe [27]**

b) **Share of flexible electric heating capacity currently used in demand response, by asset type (total capacity ~1.4 GW) [27]**

Fig. 1 (a & b)

Fig. 2 Illustration of how a smart hot water tanks, through electro thermal storage, can operate like batteries ([41]

As shown in Fig. 1a, France leads the market with installed e-HVAC assets estimated to be over 200MW: Followed by; Sweden and Norway (between 60MW and 200MW each); Finland, Germany, Netherlands, and Switzerland (between 20MW and 60 MW each); Austria and the UK, where it is estimated that less that 20MW of e-HVAC assets are installed [27]. Referring to Fig 1a, it is unsurprising France leads the market, as since the 1950s it has sought to flatten the demand curve to create a more consistent day/night base load to suit nuclear energy generation and Électricité de

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

France (EDF) has used Electrical Water Heater (EWH) aggregation along with tariff schemes incentivising consumers to use EWHs to heat water during off-peak hours [48]. According to EDF, in 2017, more than 13 million EWHs were installed in French households representing around 50% of residential hot water systems (the rest are supplied by gas and oil heating systems), accounting for an annual consumption of 20TWh and a peak demand of 8GW [48]. Importantly, overnight EWH has been a main factor behind the reshaping (flattening day and night-time peaks) of the French demand curve between 1957 and 2007 [48]. EWH aggregation schemes have also been implemented in the US; Florida Power & Light have been installing controllable electric EWHs in hundreds of thousands of homes since the 1970s [49] and since the early 1990s Great River Energy (Minnesota) have implemented an EWH aggregation system of over 110,000 homes [49, 50]. Despite the 'enormous' [42] potential of residential thermal loads to provide regulation reserve for TSO's being a proven concept [42-47], it is remarkable that less than 1% of the potential demand side flexibility of electric heating in the European residential sector is being utilised [27].

Understanding;

- the potential of EWH aggregation schemes to provide DSM/DSR flexible storage services to TSO's.
- the goal of a Demand Side Management (DSM) system is to efficiently use the available energy without the necessity of installing new transmission infrastructure, and
- most (77%, over 1.6 million in 2022) of Irish households have the facility of an electric hot water immersion heater [43] *already installed* in Domestic Hot Water (DHW) cylinders,
- that the addition of easily retrofitted low-cost equipment (circa €222/household) would convert these to 'smart' hot water cylinders, allowing them
    - to power on at times of high wind and surplus energy, while also
    - facilitating communication of the electro-thermal storage available to an aggregator to absorb excess wind energy, normally dispatched-down, and thus
- the citizens of Ireland already share a massive but unharnessed
    - dispatch-down energy source, as well as a
    - ubiquitous citizen-owned storage resource, that could be readily deployed to provide residential DSM.

The primary objective of this research is to quantify through modelling the potentials and economics of redeploying a currently wasted resources, excess wind, to create a residential EWH scheme in Ireland. The model is informed by real historical half hourly dispatch-down data, coinciding with trading intervals or settlement periods in the local electricity market [51], matched to a standardised daily hot water load particular to Irish households. Harmonisation of historical wind data to DHW load profiles has not been published previously, nor has an EWH aggregation study been carried out for Ireland. Acknowledging that Ireland suffers from among the highest rates of fuel poverty in Europe and cognisant that without adequate planning, creation of domestic market opportunities might create inequity leaving behind vulnerable consumer groups [19], this research also has the objective of reaching the furthest behind first, and hence focuses on Irish households at risk of fuel poverty as a primary aggregation group. Importantly, this the first EWH aggregation study to consider benefit to the citizen or householder as a primary aggregation parameter.

1.3 Specific Research Objectives

The management of curtailment, constraint and energy balancing pose different challenges to the network operators. Curtailment is managed at a nationwide level, whereas constraint is caused by a local and often transitory issue, while energy balancing is an emerging and growing issue in line with very high (>70%) penetrations of variable renewable energy. As complexity is greatly reduced when constraints need not be accounted for, the focus of this *primary explorative* study is on curtailed wind energy. While wind curtailment data for 2020 is available it is considered unrepresentative as human behaviours and hence associated energy profiles changed significantly due to the SARS-CoV-2 pandemic and so 2019 curtailment data for Ireland, totalling 319GWh, is used. Fig. 3 presents hourly

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

2019 curtailment data for Ireland, illustrating that the majority (73%) of curtailments, totalling 233GWh, occur at night between the hours of 10pm and 7am coinciding with low electricity demand. Since hot water is generally consumed in the daytime [52], there is more opportunity to accumulate electro-thermal storage during night-time hours before hot water is typically drawn from tanks in the morning. Understanding that the capacity of cylinders to avail of electro-thermal heat energy during the day (27%) is much less certain due to varied household consumption patterns, overnight curtailment, and its potential to heat hot water cylinders is the target of this initial feasibility study. The specific objectives of this research are to:

1. Develop, using 2019 overnight curtailed wind data, a wind allocation model to equitably redeploy overnight curtailed wind, normally dispatched-down to heat hot water in households.
2. Assess the potential of overnight curtailed wind to heat hot water to varying levels of aggregation with a focus on fuel-poor households.
3. Comment on the economic and environmental impact of this new market service.
4. Recommend policies to support using renewably powered e-HVAC services for the residential sector.

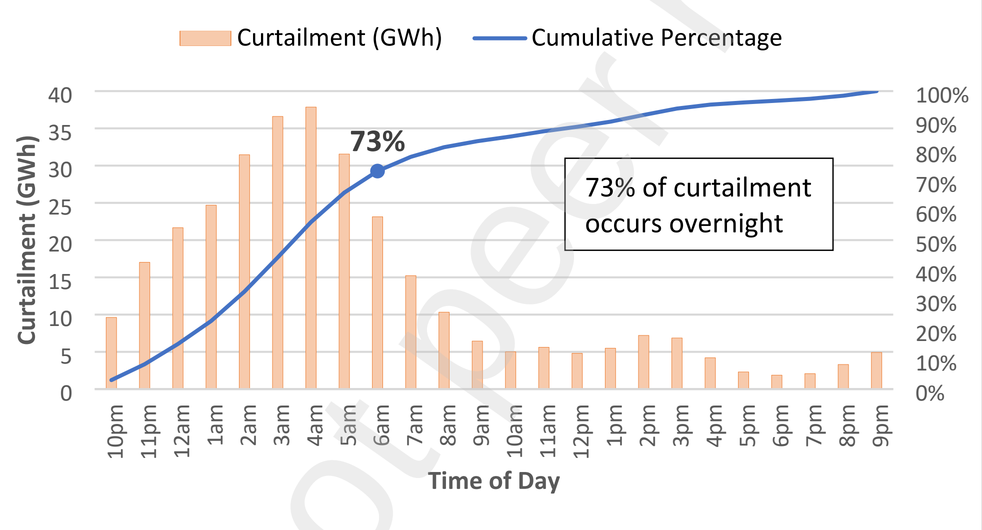


Fig. 3. Average daily curtailment distribution for Ireland in 2019.

2 Context

2 Methodology

2.1 Data

2.1.1 Domestic Hot Water Consumption Modelling

In order to harmonise historical dispatch-down wind data to DHW load profiles or as put by Mabina et al. [40], enable 'sustainability matchmaking', it is necessary to establish DHW consumption profiles in households. Hot water consumption patterns vary by region and climate, daily DHW consumption in non-fuel poor dwellings varies from a low of 43 litres/day in Finland to a high of 256 litres/day in Florida, while the global average is 202 litres/day [53]. Hot water consumption patterns also vary for days of the week and annual patterns vary for seasons [33-35, 54]. Some studies [55-57] report the day of the week and the season to have distinct effects on water demand with significant factors being outdoor temperature and precipitation levels, for instance, DHW is found to increase on hot days in some regions (New York), but reduce in others (Florida). While others [58] found no significant decrease in consumption during weekends and no strong correlation with weather conditions, neither outdoor temperature nor precipitation levels (German speaking regions in Switzerland). Hot water

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

Preprint not peer reviewed

consumption profiles further vary by; (i) occupancy profile [59, 60], older people flush the toilet more often and young children more often take a bath, while teenagers take the longest showers [60], and (ii) behaviour, driven, for instance, by environmental concerns and socioeconomic status [53, 61].

Residential hot water consumption profiles have been studied for single family dwellings in the US [62], UK [63], Netherlands [60], Germany and Switzerland [64, 65], Finland [66] and Sweden [67], while consumption profiles of apartments have been characterised in Greece [68]. Almost all models vary in their modelling approach [33] being *inter alia* standards-based [69, 70], data-collected [37, 38, 71], stochastic [60, 64, 65, 67, 72, 73], behavioural [62, 74], data-learning [75], time-series [39, 68] and data-driven [36]. Ritchie et al., 2021 [33] reviewed numerous EWH aggregation studies [36, 39, 60, 64, 67-75] to find that most neglected (i) differences between users, (ii) temporal variations such as the season and the day of the week, and (iii) in respect of modelling, were not fully autonomous.

In general, hot water usage is largely simultaneous [33-36, 53] with two peaks, one in the morning and one in the evening with the balance spread over the day. Peak characteristics vary by country, for instance, in Finland, the peak is higher in the evening and lower in the morning whereas the behaviour is the opposite in Germany [58] and in Ireland [76].

Importantly, a trend of DHW savings is reported [53, 59] in the last decades and so models must be periodically updated [58]. Models also become more accurate if they are multi-parameter, considering age and occupation [77]. Other factors to consider are holidays and occasions [57]. In 2021, Ritchie et. al [78], derived, from an analysis of 77 dwellings in South Africa, a multi-parameter probabilistic data-driven model that statistically modelled hot water profiles, over a weather year, and a simulator that used the model to generate seasonal hot water usage profiles; this study provides a robust basis for modelling hot water consumption profiles *when measured data is available* as a basis for the model.

2.1.1.1 Domestic Hot Water Consumption in non-fuel poor households

Hot water consumption patterns for Irish households are not available in the literature. Ireland's national energy authority, the Sustainable Energy Authority of Ireland (SEAI) has funded a study that is being carried out, at the time of writing, by Ireland's Economic and Social Research Institute (ESRI) in cooperation with a technology provider, climote ltd.; results are due to be published in Q4 of 2023 [79]. In the absence of an Irish study, the closest region climatically and geographically is the UK. A hot water consumption study [63] of significance, used in many DHW modelling studies [37-39], was carried out by the UK Energy Saving Trust in 2006. Domestic hot water consumption in 112 dwellings were recorded for one year at ten-minute intervals. When water run-off was detected, the sampling rate increased to five seconds. The data was then resampled at constant intervals of 1, 2 and 3 hours. This study found [63];

- the mean water consumption rate per UK household to be 122 litres/day with a 95% confidence interval of ±18 litres/day.
- hot water heating time to be 2.6 hours/day, estimated with a 95% confidence interval of ± 0.35 hours/day, finding that some households heat water as and when it is required, and the remainder generally heat water between 8:00am and 10:00am, and again between 6:00pm and 11:00pm.
- Storage temperatures to be significantly below the widely assumed value of 60°C, with a mean value of 51.9°C estimated with a 95% confidence interval of ±1.3°C.
- that a key factor influencing consumption is the number of occupants.

The typical hot water consumption profile for UK dwellings published in the study [63] did not account for days of the week, seasonal variations or occupancy.

Fig. 4 illustrates a *typical* arrangement of hot water cylinder components installed in Irish households. The cylinder presented is sufficient to store the average daily hot water requirement, estimated by

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

SEAI at 9.63kWh/day [80]. At a boiler efficiency of 85% and an average hot water heating time of 2.6 hours per household (as per UK Energy Saving Trust study [63]), this equates to 129 litres/day heated to 51.9°C or 108 litres heated to 60°C, noting that these figures ignore energy poverty and affordability, assuming householders can afford to heat water for an average of 2.6 hours/day. Indeed, in the same report [80], SEAI note strong policy drivers in favour of gathering improved hot water usage data along with electricity use for hot water particularly relating to energy poverty and affordability. Referring to Fig. 4, 'cold' (c10°C) water flows up through an unseen internal pipe at the base of the cylinder, past an indirect heating coil supplied by an oil and sometimes gas-fired boiler. The water then flows past an electrical immersion which can act as a backup or as an alternative to the boiler as required and, in some instances, may be the sole source of energy when lower rate night-time electricity tariffs are availed of. Typically, electrical immersions are rated at 3 kilowatts (3kW) supplied with a 230-volt single-phase supply limited to 13 amperes (230V and 13A). A standard 3kW electrical immersion will consume 9 kWh of electricity in 3 hours to generate 155 litres of 60°C hot water if heated from 10°C i.e., much of the average daily hot water requirement of 9.63 kWh for standard (non-fuel poor) Irish households [49].

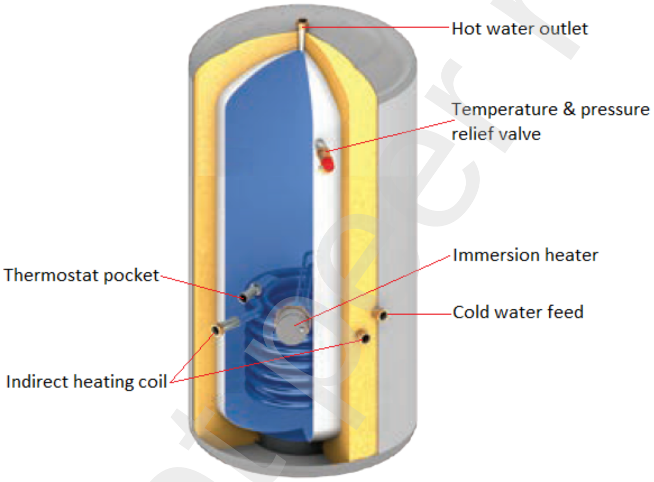


Fig. 4. Hot water cylinder configuration (120 to 210 litres nominal capacity), adapted from [81].

To convert the cylinder shown in Fig.4 to a smart cylinder the following would be retrofitted:

- Temperature sensor(s) to accurately estimate the available heat capacity within the cylinder so that it is known whether or not surplus energy can be safely utilised throughout a specified timeframe;
- Telecommunications to;
  - transmit a signal to an aggregator that the cylinder can accommodate electro-thermal energy,
  - receive a command from the aggregator activating an electrical relay to switch immersion on or off as necessary.

The above listed functionality is provided by smart thermostats available on the Irish market, for instance, as manufactured by technology provider, climote Ltd. [82], at an estimated installed cost of €222/device.

2.1.1.2 Domestic Hot Water Consumption and Storage in households considered at risk of fuel poverty

Section 2.1.1.1 details typical hot water consumption profiles in non-fuel poor households, however fuel poor and non-fuel poor households consume hot water differently. The British Research Establishment (BRE) [83], in a 2018 UK study, found fuel poor households were significantly (60%),

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

Preprint not peer reviewed

more likely, than non-fuel poor households (45%) to be taking less than one shower and/or bath per person per day. The study also found that households in fuel poverty were less likely (21%) than those not in fuel poverty (31%) to take a shower and/or bath once per person per day. Interestingly this same study found that the fuel poor were less likely (84%) to heat their water with a central heating system, compared with the non-fuel poor (92%), and the fuel poor were almost twice as likely (13%) to heat their water with an electric immersion heater than the non-fuel poor (7%). Further analysis of households with showers revealed that fuel poor households were more likely (47%) to use an electric shower than non-fuel poor households (35%) and were less likely to use a shower that was pumped from the main hot water system (10% compared with 16%). Regrettably, the BRE study [83] did not publish hourly water consumption patterns for the fuel-poor households studied.

As stated, there has been an overall trend of DHW savings in the last decades [53, 59] requiring models to be updated periodically [58]. Apropos, since the 2018 BRE study, Ireland, whose predominant fuel source is oil, has seen the average fuel price to households (€cent/kwh) [84] rise for electricity (22%), gas (32%) and oil (70%), leading to more recent articles on fuel poverty referring to householders going without heating or hot water [85, 86] altogether. These findings [85, 86] are supported by a public survey in Ireland of just under 300 respondents carried out in 2020 [86] that found almost half of fuel poor households in Ireland suffer from prolonged cold because they cannot afford to turn on their heat, highlighting that fuel-poor householders were sacrificing food and clothing to pay for heat, and that children and parents sometimes sleep in living rooms, wrapping in quilts during the day or staying in bed all day. The study [86] reported that, to ration their energy use, some fuel-poor householders routinely went without heat or electricity, and many allowed themselves very limited hot water, referring to the depth and breadth of fuel poverty in Ireland as a ‘silent crisis’.

EnergyCloud [87] is a social enterprise in Ireland and the UK whose mission is to create solutions to divert surplus renewable energy – which would be otherwise wasted – to Irish homes in fuel poverty. At time of writing, EnergyCloud has a 40-household EWH heating pilot underway in Ireland. Accurate weather forecasting along with a smart grid dashboard [88] published by Ireland’s TSO allows EnergyCloud to predict a high probability of excess wind occurring overnight. When overnight excess wind is predicted, participants are messaged at 5pm on the evening before to let them know to expect to wake to a free tank of hot water and to forgo heating their hot water tank, if intended. Communication with the householder ensures that the tank is as ‘cold’ as possible at 10pm on the night preceding the likely curtailment event. Data from the pilot is yet unpublished but it is informally reported that scheme participants/householders are beginning to “storm chase” [89], paying attention to high wind events with the expectation of receiving a free hot water tank. The methodological approach thus adopted in this *initial* feasibility study thus assumes hot water tanks are ‘cold’ at 10pm on the nights preceding curtailment events. This is acknowledged as a significant limitation of this study. This crude approach will be refined;

i. when hot water consumption patterns for Irish households are published by the ESRI [79], or more ideally, as the focus is on fuel-poor dwellings specifically,
ii. on EnergyCloud pilot data, when published.

Once measured data for Irish households, ideally fuel-poor Irish households, is available, differing water consumption/tapping profiles can be generated using a multi-parameter methodology as defined by Ritchie et. al, 2021 [33], or with next generation machine learning methodologies proposed by Mabina et al., 2021 [40] and Bakker et al., 2008 [75] that might be used to predict, with knowledge of the expected weather and the previous day’s heat profile, the water demand for the following day. This limitation and future research opportunities are further explored in Sections 4 and 5 of this paper.

2.1.2 Curtailed wind data

Further to Fig. 1, the number of nights that overnight wind curtailment was present was examined. It is seen that wind curtailment was *not* present during any half-hour between 10pm and 7am for most

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

(61%) or 222 nights during 2019. Notwithstanding when curtailed wind was observed in the other (39%) 143 nights of the year, it *was* present for a significant duration, as 85% or 122/143 of nights saw wind curtailment for at least 6 half-hours – the time required to heat an assumed cold tank fully to 60°C.

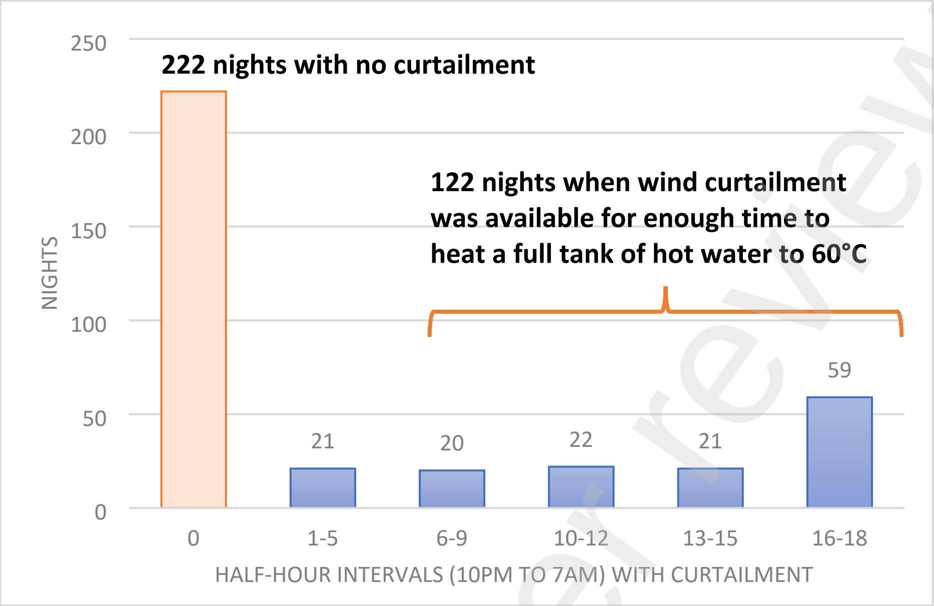


Fig. 5 Nightly instances of curtailment (10pm to 7am) for Ireland in 2019.

To understand the distribution of 'curtailment nights' across the year, the number of weeks where a curtailment night arose in 2019 was examined. Referring to Fig. 6, it is seen that although wind curtailment was not observed overnight for 6 calendar weeks, a night of curtailment was observed for the remaining 46 (88%) calendar weeks of the year.

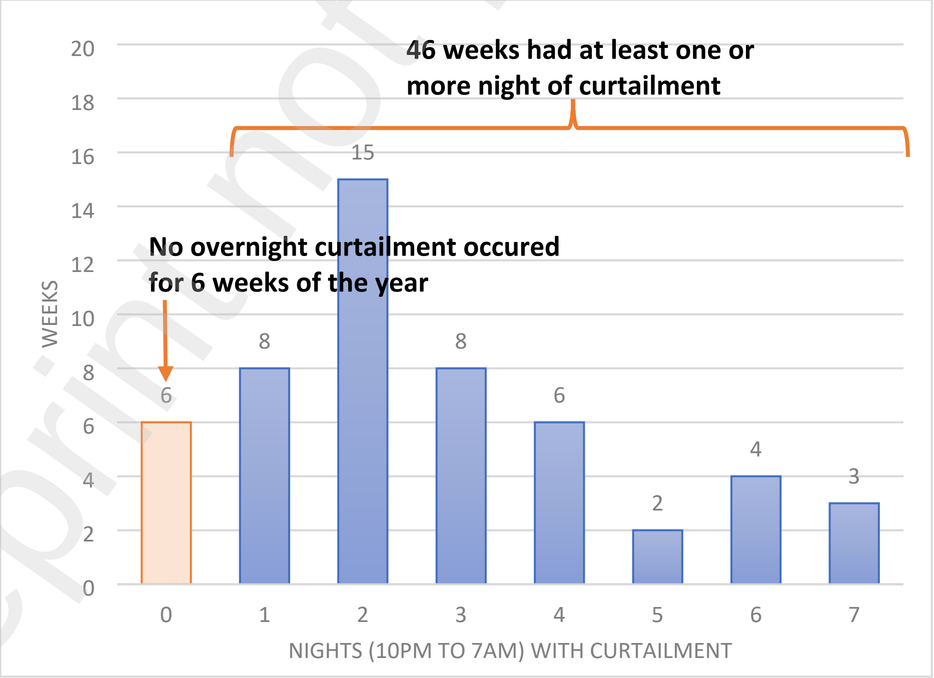


Fig. 6. Weekly instances of curtailment (10am to 7am) for Ireland in 2019.

2.1.3 Fuel poor aggregation group

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

In 2015, the Irish Government commissioned an in-depth bottom-up analysis of energy poverty in Ireland [90]. Based on the objective method [90] of calculation, 1 in 4 (28%) or up to 461,000 households were potentially in fuel poverty in 2015 [91]. At the time of modelling (2021) and while more recent data on fuel poverty, published by the ESRI and available through the Central Statistics Office [92] was available, the calculations are based on the expenditure method. The expenditure method considers a household to be in energy poverty, if said household spends more than 10% of overall household income on energy services. This metric can "give an incomplete picture of energy poverty" as households living in deprivation may not be able to afford to spend 10% of their income on energy, thus living in inadequately heated homes, and who are not captured by the expenditure method; moreover, more affluent households may spend over 10% of their income on energy costs [91]. The objective method for calculating fuel poverty models the level of fuel expenditure required by a typical household to keep their home heated to the levels recommended by the World Health Organisation and compares this to household income in an attempt to calculate exposure to energy poverty; considered in the Government of Ireland's "Spending Review 2020 - *Social Impact Assessment - SEAI Programmes Targeting Energy Poverty"* [91] to be a more robust assessment for energy poverty and thus the figure used in this research hypothesis.

2.2 Wind Curtailment Allocation Model

2.2.1 Preliminary model boundary parameters

While EWH aggregation schemes exist in other counties, as stated in Section 1, no residential demand response scheme is operational in Ireland. For this initial feasibility study, the allocation of curtailed wind energy is based on the following preliminary boundary parameters:

1) Only wind curtailed between 10pm and 7am overnight is applied, the rationale for targeting overnight curtailed wind initially is as follows:
    a. >70% of curtailment happens during night-time hours (see Fig. 1).
    b. Night-time use-of-system charges are ¼ of day-time use-of-systems charges;
        i. meaning any rebate applied to account for the household meter, turning with the application of redeployed electrical energy, relating to SNSP limits and synchronous plant base-load costs will be minimised, and, for the same reason
        ii. if an aggregator, focused on fuel-poor householders seeks contributions from energy generators and suppliers, contributions will go further during night-time hours as the electricity price is lower, meaning the aggregator will be able to provide a higher subsidy against night-time tariff rates – to render the delivered energy free or at a significantly lower than retail cost.
    c. In favour of day to night load shifting, market participants and Ireland's Commission for Regulation of Utilities (CRU) will be more supportive of scheme targeted for night-time hours initially.
    d. Simplifies water consumption profiles as little draw-off is universally reported across all hot water consumption studies across regions during night-time hours.
2) A minimum activation period 30 minutes and multiples thereof is applied at each 3kW immersion to limit excessive relay switching and to coincide with the available data and electricity market trading intervals.
3) Each immersion remains energised across multiples of 30 minutes so that, if possible, only one relay activation and deactivation signal is necessary from the aggregator while individual households receive as much useful hot water as possible when allocated energy [48].
4) As detailed in Section 2.1.1.2, each household is allocated up to 6 half-hour time periods receiving 9kWh to almost meet the national daily average hot water consumption figure of 9.63kWh [46] at 60^{o}C. The model allocates 1.5kWh of energy to as many household immersions as possible in a 30-minute period, it hence prioritises households who have

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

Preprint not peer reviewed

already received an allocation so as to provide a household with a full tank and hence a useful amount of hot water periodically.

5) Step 4 ensures that the tank is 'scalded' to reduce the risk of legionella growth.

2.2.2 Wind allocation methodology

Facilitating an articulation of the wind allocation model methodology, Table 2 illustrates the potential allocation of wind curtailment to 200,000 Irish households overnight (10pm to 7am) on a randomly chosen night of the 12th of January 2019, each half hour in this sample allocation table may be explained as follows:

- **10pm to 10:30pm:** it is seen that wind curtailments of 92MWh occurred which divided by 1.5kWh per immersion equates to sufficient energy for 61,322 household DHW immersions (92000kWh/1.5kWh).
- **10:30pm to 11pm:** there was only enough energy to deliver 1.5kWh (1 allocation) of energy to 5,488 homes.
- **11pm to 11:30pm:** no curtailment occurred and thus no energy was allocated.
- **11:30pm to 12pm:** there was sufficient energy for 77,033 homes, therefore 55,834 households received a second allocation, 5489 receive a third allocation while 15,710 (77,033-61322) received an allocation of wind energy for the first time, noting in Table 2 that homes identified from;
    - 1 to 5,488 have availed of power for three 30-minute periods,
    - 5,489 to 61,322 have availed of power for two 30-minute periods,
    - 61,323 to 77,033 have been supplied with energy for the first time.
- **12:00am to 1:00am:** any available energy was allocated in a similar manner to that described for the previous time periods.
- **1:30am to 2am:** it is seen that the homes identified from 1 to 5,488 no longer receive energy having already received the maximum of 6 allocations as noted by the allocation count at the base of the table. It is worth noting that even though there is sufficient energy at this time for 212,286 homes, households identified from 5,489 to 200,000 (or up to the total households within the identified aggregation) received energy.
- **2:00am to 4:00am:** available wind curtailment was allocated to the remaining homes until they each have been provided with 9kWh or 6 allocations of 1.5kWh of renewable electricity.
- **4:30am to 6:30am:** even though significant energy was available this was left unused as all 200,000 homes in the identified aggregation have been provided with their maximum allocation.

On the night of January 12th, more than 200,000 smart hot water cylinders would need to be available to avail of curtailed night-time wind energy available on that particular night, conversely, as shown in Table 3 on the night of January 3rd, 2019, when there was relatively low curtailment only 24,590 homes would receive excess wind allocations with none receiving 6 allocations or 9kWh equating to a full tank of hot water.

To establish the capacity of night-time curtailed wind energy to heat domestic hot water tanks, the redeployment of night-time curtailed wind energy was modelled for various populations of consumers until it was observed that all of the available night-time curtailed wind energy available in 2019 was utilised as detailed in Section 3: Results & Analysis.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

Table 2

Potential allocation of curtailment to 200,000 homes overnight on 12th January 2019.

Time	Curtailment [MWh]	Potential Households [-]	**Household Allocations and Identifiers**													
22:00	92.0	61,322	**1**	*5,488*	*5,489*	**61,322**										
22:30	8.2	5,488	**1**	**5,488**												
23:00	0	0														
23:30	115.6	77,033	**1**	*5,488*	*5,489*	*61,322*	*61,323*	**77,033**								
00:00	210.5	140,321	**1**	*5,488*	*5,489*	*61,322*	*61,323*	*77,033*	*77,034*	**140,321**						
00:30	259.2	172,791	**1**	*5,488*	*5,489*	*61,322*	*61,323*	*77,033*	*77,034*	*140,321*	*140,322*	**172,791**				
01:00	275.6	183,700	**1**	*5,488*	*5,489*	*61,322*	*61,323*	*77,033*	*77,034*	*140,321*	*140,322*	*172,791*	*172,792*	**183,700**		
01:30	318.4	212,286			**5,489**	*61,322*	*61,323*	*77,033*	*77,034*	*140,321*	*140,322*	*172,791*	*172,792*	*183,700*	*183,701*	**200,000**
02:00	323.0	215,357					**61,323**	*77,033*	*77,034*	*140,321*	*140,322*	*172,791*	*172,792*	*183,700*	*183,701*	**200,000**
02:30	346.6	231,058							**77,034**	*140,321*	*140,322*	*172,791*	*172,792*	*183,700*	*183,701*	**200,000**
03:00	397.6	265,079									**140,322**	*172,791*	*172,792*	*183,700*	*183,701*	**200,000**
03:30	427.3	284,835											**172,792**	*183,700*	*183,701*	**200,000**
04:00	462.1	308,044													**183,701**	**200,000**
04:30	455.1	303,414														
05:00	447.6	298,430														
05:30	449.3	299,564														
06:00	440.3	293,555														
06:30	460.0	306,668														
		Allocation Count	6	6	6	6	6	6	6	6	6	6	6	6	6	6

Table 3

Potential allocation of curtailment to 200,000 homes overnight on 3rd January 2019.

Time	Curtailment [MWh]	Potential Households [-]	**Household Allocations and Identifiers**					
22:00	0	0						
22:30	0	0						
23:00	0	0						
23:30	0	0						
00:00	0	0						
00:30	0	0						
01:00	0	0						
01:30	0	0						
02:00	29.3	19,524	**1**	*4,064*	*4,065*	**19,524**		
02:30	36.9	24,590	**1**	*4,064*	*4,065*	*19,524*	*19,525*	**24,590**
03:00	6.1	4,064	**1**	**4,064**				
03:30	0	0						
04:00	0	0						
04:30	0	0						
05:00	0	0						
05:30	0	0						
06:00	0	0						
06:30	0	0						
		Allocation Count	3	3	2	2	1	1

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

3 Results & Analysis

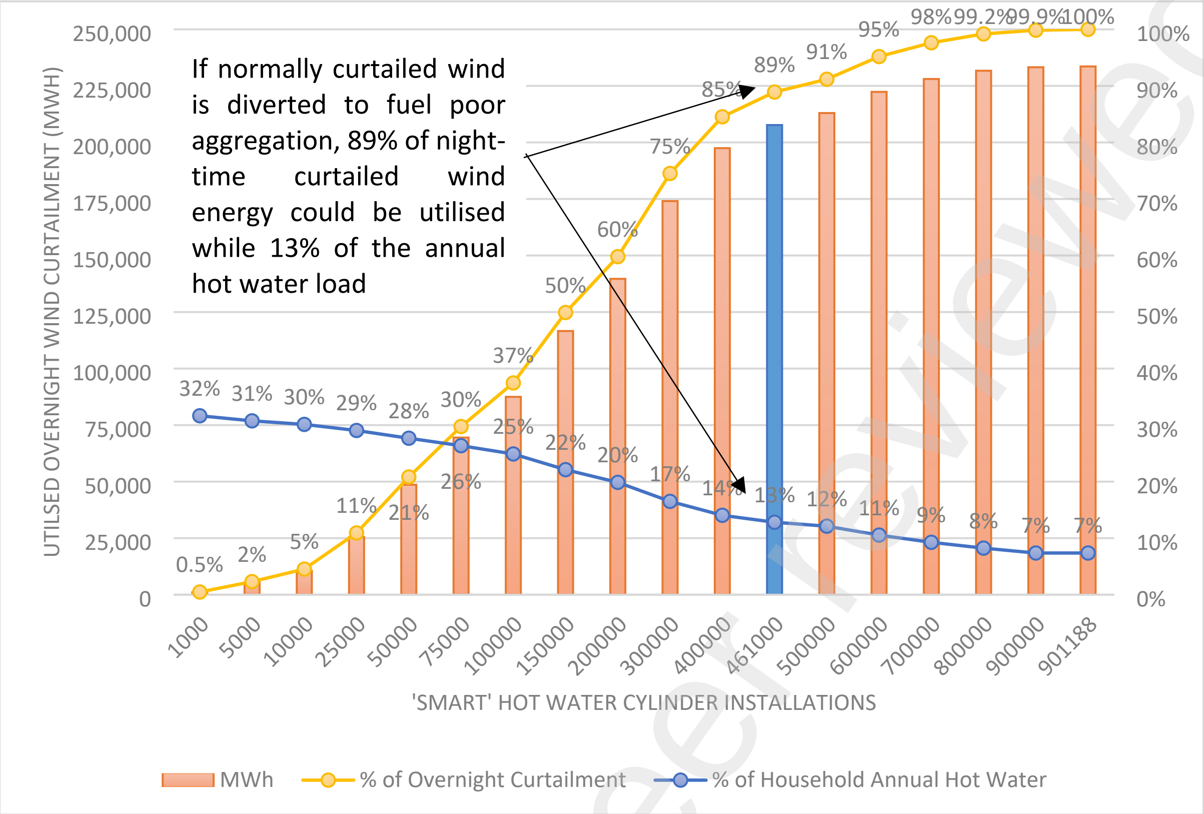


Fig. 7. Utilised overnight wind curtailment for various 'smart' hot water cylinder installations.

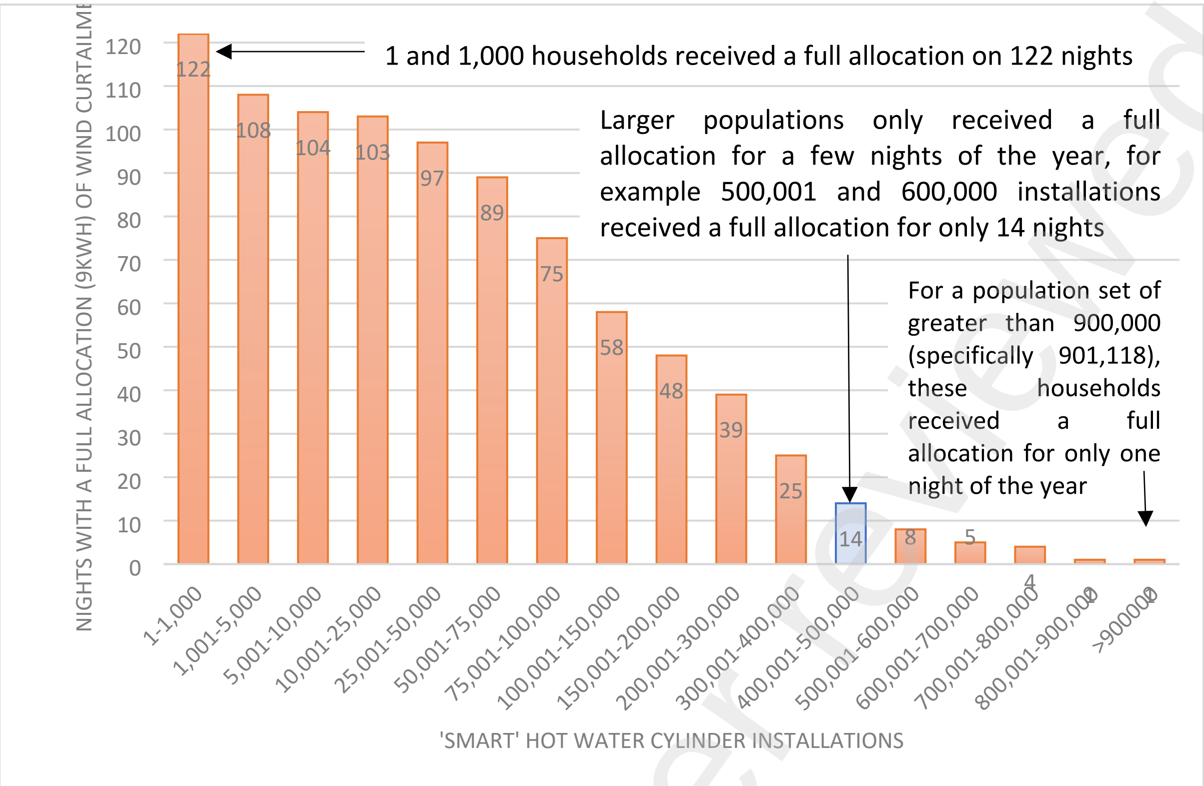
3.1 *Nightly allocation of curtailed wind energy*

Fig. 8 illustrates the number of nights by aggregation set in 2019 within which a full allocation of 9kWh of wind curtailment may have been provided to a household within that set. Referring to Fig. 8 between:

- 1 and 1,000 households received a full allocation on 122 nights;
- 1,001 and 5,000 households received a full allocation on 108 nights;
- 5,001 and 10,000 households received a full allocation on 104 nights;
- and so on until it is apparent that the larger populations only received a full allocation for a few nights of the year, for example 500,001 and 600,000 installations received a full allocation for only 14 nights or 11% of the nights in which wind curtailment was present, while for a population set of greater than 900,000 (specifically 901,118), these households received a full allocation for only one night of the year - coinciding with the Christmas holiday period occurring on Sunday, 29th December 2019 when presumably strong winds and less industrial activity led to significant curtailment.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515



1 and 1,000 households received a full allocation on 122 nights

Larger populations only received a full allocation for a few nights of the year, for example 500,001 and 600,000 installations received a full allocation for only 14 nights

For a population set of greater than 900,000 (specifically 901,118), these households received a full allocation for only one night of the year

Fig. 8. Nights with a full allocation (9KWh) of energy for various population sets.

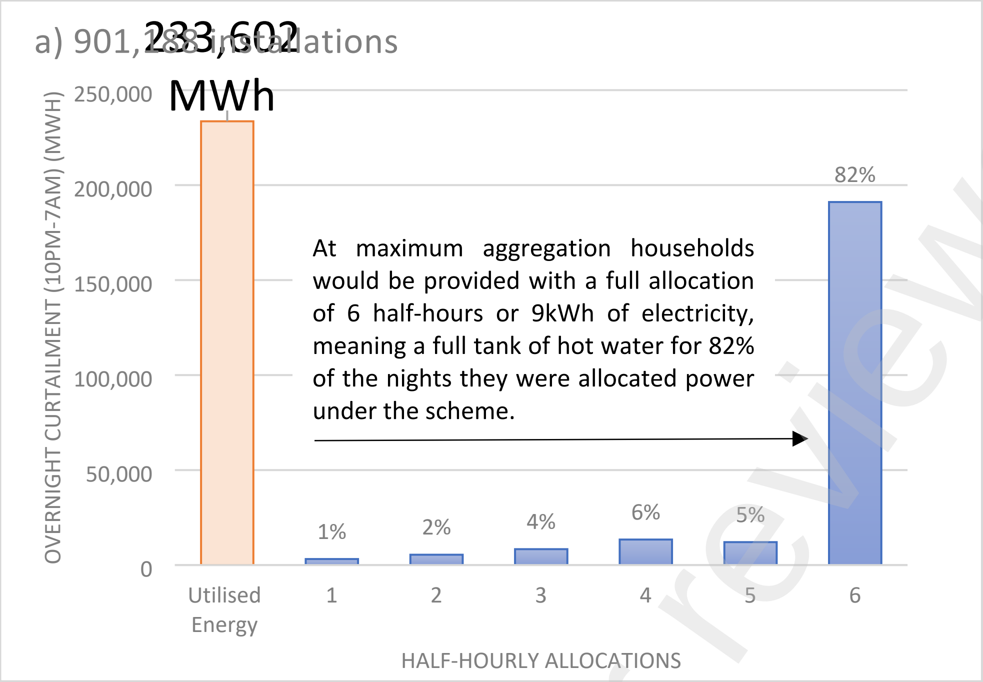
Following from Fig. 8, Fig.'s 9 (a&b) illustrate nightly allocation of curtailed wind energy for the maximum aggregation of 901,188 (based on 2019 figures) to a minimum aggregation of 1000 dwellings.

When 901,188 are aggregated, only 7% of the annual hot water demand is met (see Fig. 7), while 234GWh of curtailed wind (73% of curtailed wind in 2019), normally wasted, is utilised. Fig. 9a illustrates that when households within this aggregation are allocated energy, they would be provided with a full allocation of 6 half-hours or 9kWh of electricity, meaning a full tank of hot water for 82% of the nights they were allocated power under the scheme.

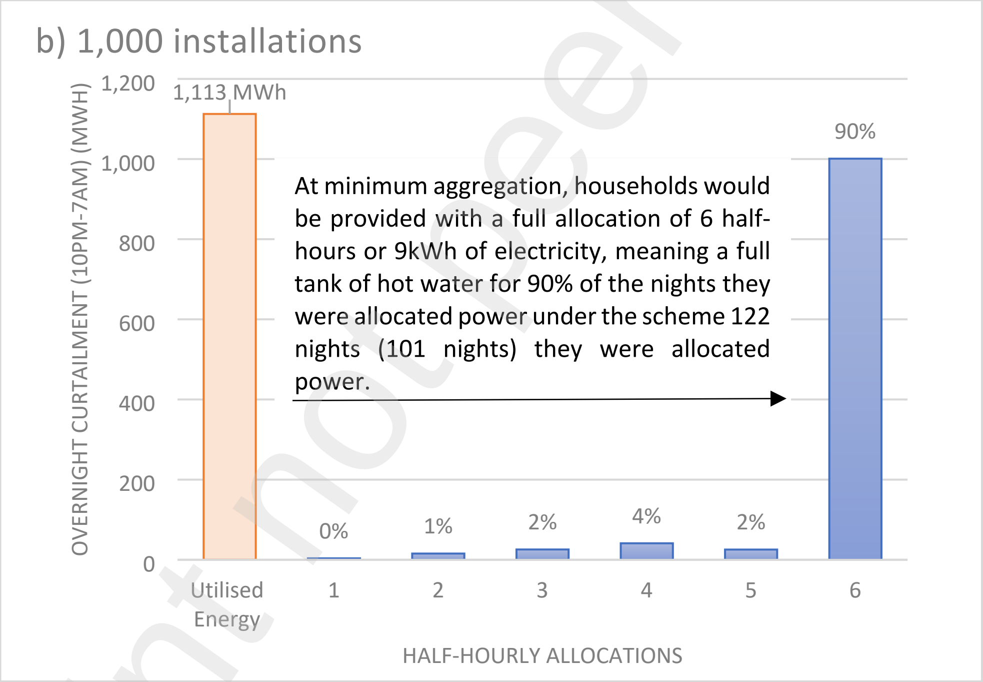
Whereas, if 1,000 households are aggregated and referring to Fig. 9b, 32% of the hot water demand could be met, while 1GWh of curtailed wind (0.3% of curtailed wind energy in 2019) would be redeployed, with households within the aggregation receiving a full tank of hot water for 90% of the 122 nights (101 nights) they were allocated power.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515



At maximum aggregation households would be provided with a full allocation of 6 half-hours or 9kWh of electricity, meaning a full tank of hot water for 82% of the nights they were allocated power under the scheme.



At minimum aggregation, households would be provided with a full allocation of 6 half-hours or 9kWh of electricity, meaning a full tank of hot water for 90% of the nights they were allocated power under the scheme 122 nights (101 nights) they were allocated power.

Fig. **9.** Utilised energy and distribution of half-hourly allocations

It can be concluded therefore, that under an aggregation scheme distributing normally curtailed wind energy *as a service*, that when individual households are allocated energy, they will typically (≥82%) be provided with a full allocation of 9kWh or a tank of hot water irrespective of the number of households aggregated. This can be attributed to the fact that the model parameters ensure, where possible, that immersions in an individual household remain energised until a full allocation has been received along with the phenomenon of when instances of wind curtailment typically occur, they typically occur for much of the night (windy nights).

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

3.2 Weekly allocation of curtailed wind energy

As this research has a focus on impacting households at risk of fuel poverty, the analysis progressed to a pragmatic assessment of the extent to which a full tank of hot water can be provided for at least one night of the week so that important cleaning, bathing, and hygiene tasks within each home can be catered for on a weekly basis. The benefit of which might be much more apparent to fuel poor households who are known to limit hot water use [86]. The results of the Wind Curtailment Allocation Model are thus assessed to observe the frequency at which households receive at least one full tank of hot water for the 46 weeks of the year when curtailment was observed (Ref Fig. 6). As shown in Fig. 10, it is seen that the smallest (N=1000) population set received a full allocation for 45/46 (97.8%) weeks, whereas the largest population set (N=901,188) received such an allocation for 6/46 (13%) weeks that curtailment was available.

This latter observation should not be confused with Section 3.1/Fig. 8 which showed that there was only one *night* of the year when a full allocation could be delivered to the largest population set, because within a *weekly* timeframe there are seven nights in which to provide households with a full allocation of energy on at least one night of the week. For example, in the week beginning the 3rd of February 2019 there was curtailment on six of seven nights with the potential to provide energy to over one million cylinders.

Thus, if a roll-out of such technology is to be considered to the larger population sets from say 500,000 households and beyond, not only would they receive a small proportion of their annual hot water demand (≤12% in Fig. 7) these households would only receive at least one night with a full allocation of energy for less than a third of the 46 weeks in which curtailment occurred (≤32.6% in Fig. 10). Whereas if less households, say 5,000, are targeted, they would receive almost a third of the annual hot water demand (31% in Fig. 7) and at least one night with a full allocation of energy for 44/46 weeks (95.7% in Fig. 10) in which curtailment occurred. Therefore, there is a greater observable effect on hot water provision for individual householders if less installations are aggregated.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

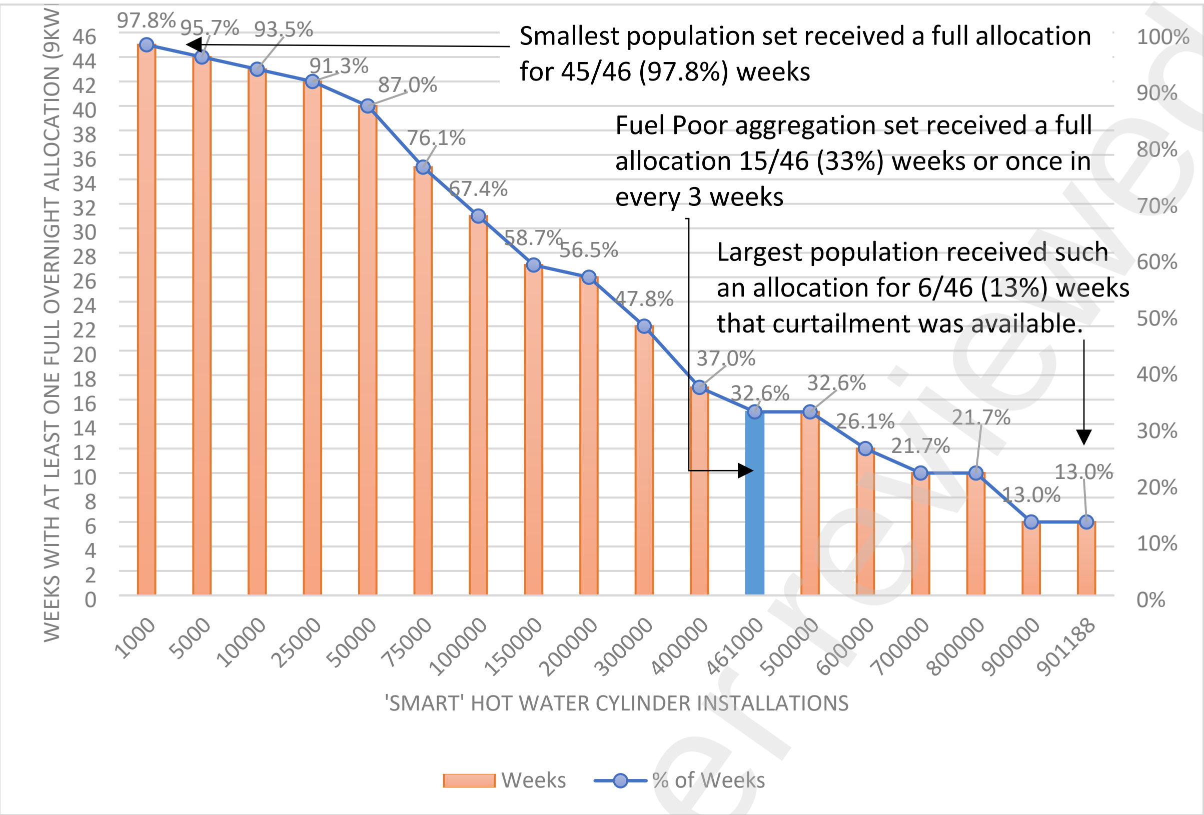


Fig. 10. Weeks with at least one full overnight allocation of wind curtailment.

3.3 *Economic and Environmental Analysis*

The Irish householder is estimated to consume 3,515kWh of energy annually to heat hot water [80]. Referencing Table 3, this costs the Irish householder an averaged €284/annum emitting an average of 702kg/CO_2 depending on heating system and fuel choice. There were 1.86M occupied dwellings in Ireland in 2022 [94], therefore the total energy cost borne by the citizens of Ireland amounts to €529M while the carbon emissions associated amount to 1.3MtCO_2/annum. Table 3 also details, as a function of aggregation size and hence percentage of hot water load met (cross reference Fig. 7), DHW fuel costs and resultant carbon emissions per household at the prevailing SNSP of 75%. It is seen that household cost and CO_2 emission savings are modest, ranging from;

- 6% or €16/38kg$C0_2$/annum at the maximum aggregation size of 901,188 dwellings to
- 20% or €57/136kgCO_2/annum at an aggregation of 100,000 dwellings.

Lowering averaged household DHW bills from;

- €284/annum to €278/annum, at the maximum aggregation, and
- €284/annum to €227/annum at an aggregation of 100,000 households.

It must be again highlighted here, that the model assumes *a standardised water profile*, assuming householders can afford to heat hot water in the first place, it is known that in fuel-poor homes, householders limit generation of hot water to limit financial outlay, therefore there might be no savings realised as water is not being heated in the first instance, this is a limitation of this work that will be refined in future research.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

Household cost and CO_2 emission savings are modest, ranging from 6% or €16/38kg$C0_2$/annum at the maximum aggregation size of 901,188 dwellings to 20% or €57/136kgCO_2/annum at an aggregation of 100,000 dwellings.

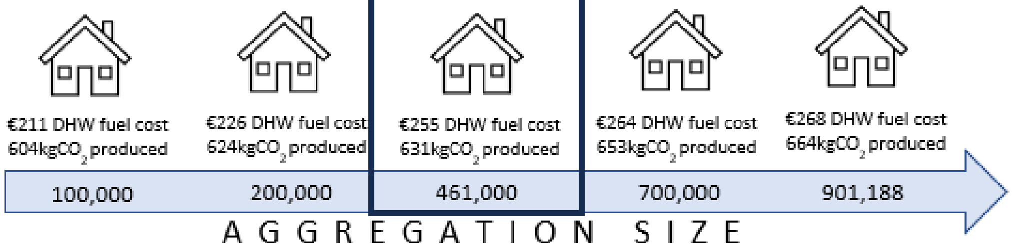
Table 3 Energy Cost and CO_2 emissions associated with delivered and deployed domestic hot water as a function of aggregation size (cross-reference Fig. 7)

			Fuel cost and CO_2 emissions			Houshold Cost and CO_2 emissions		Shadow Price Carbon/1000kgCO_2			Cost and CO_2 emissions saving realised from redeployment of excess wind to heat hot water											
											% Water load											
											100%				25%				20%			
								2020	2030	2050	SNSP 75%		SNSP 95%		SNSP 75%		SNSP 95%		SNSP 75%		SNSP 95%	
			%	c/kWh	gCO_2/ kWh	€	kgCO_2	€ 32	€ 100	€ 265	€	kgCO_2	€	kgCO_2	€	kgCO_2	€	kgCO_2	€	kgCO_2	€	kgCO_2
Fuel	Electricity	Day	9%	22	324.5	€ 773	1141	€ 37	€ 114	€ 302	€ 712	961	€ 761	1105	€178	241	€ 190	277	€142	192	€152	221
		Night	2%	10	324.5	€ 352	1141	€ 37	€ 114	€ 302	€ 290	961	€ 339	1105	€ 73	241	€ 85	277	€ 58	192	€ 68	221
	Natural Gas		25%	7.02	204.7	€ 247	720	€ 23	€ 72	€ 191	€ 185	540	€ 234	684	€ 46	135	€ 59	171	€ 37	108	€ 47	137
	Solid Fuel	Coal	4%	5.98	340.6	€ 210	1197	€ 38	€ 120	€ 317	€ 149	1017	€ 198	1161	€ 37	254	€ 49	290	€ 30	203	€ 40	232
		Peat	5%	7.09	355.9	€ 249	1251	€ 40	€ 125	€ 332	€ 188	1071	€ 237	1215	€ 47	268	€ 59	304	€ 38	214	€ 47	243
	Oil		21%	5.98	257	€ 210	903	€ 29	€ 90	€ 239	€ 149	723	€ 198	867	€ 37	181	€ 49	217	€ 30	145	€ 40	174
	Renewables	Biomass	13%	5.96	25	€ 209	88	€ 3	€ 9	€ 23	€ 148		€ 197	52	€ 37		€ 49	13	€ 30		€ 39	10
		Solar	6%					€ -	€ -	€ -												
		Geo	15%	10	162.25	€ 352	570	€ 18	€ 57	€ 151	€ 290	390	€ 339	534	€ 73	98	€ 85	134	€ 58	78	€ 68	107
	Energy Cost and associated CO_2 emissions		per household		1	€ 284	703	€7	€22	€180	€ 226	545	€ 273	669	€ 57	136	€ 68	167	€ 45	109	€ 55	134
			Total (in millions) for various aggregrat-ions		100,000	€ 28	70	€2	€7	€19	€ 23	55	€ 27	67	€ 6	14	€ 7	17				
					200,000	€ 57	141	€4	€14	€37	€ 45	109	€ 55	134					9	22	11	27
					461,000	**€ 131**	**324**	**€10**	**€32**	**€86**	**€ 104**	**251**	**€ 126**	308								
					700,000	€ 199	492	€16	€49	€130	€ 159	382	€ 191	468								
					901,188	€ 256	633	€20	€63	€168	€ 204	491	€ 246	603								
					1,860,000	€ 529	1307	€42	€131	€346	€ 421	1014	€ 507	1244								

				Cost and CO_2 emissions saving realised from redeployment of excess wind to heat hot water											
				% Water load											
				13%				9%				7%			
				SNSP 75%		SNSP 95%		SNSP 75%		SNSP 95%		SNSP 75%		SNSP 95%	
			gCO_2/ kWh	€	kgCO_2	€	kgCO_2	€	kgCO_2	€	kgCO_2	€	kgCO_2	€	kgCO_2
Fuel	Electricity	Day	324.5	€ 93	125	€ 99	144	€64	87	€68	100	€50	68	€53	78
		Night	324.5	€ 38	125	€ 44	144	€26	87	€30	100	€20	68	€24	78
	Natural Gas		204.7	€ 24	70	€ 30	89	€17	49	€21	61	€13	38	€16	48
	Solid Fuel	Coal	340.6	€ 19	132	€ 26	151	€13	91	€18	104	€10	71	€14	81
		Peat	355.9	€ 24	139	€ 31	158	€17	96	€21	109	€13	75	€17	85
	Oil		257	€ 19	94	€ 26	113	€13	65	€18	78	€10	51	€14	61
	Renewables	Biomass	25	€ 19		€ 26	7	€13		€18	5	€10		€14	9
		Solar													
		Geo	162.25	€ 38	51	€ 44	69	€26	35	€30	48	€20	27	€24	37
	Energy Cost and associated CO_2 emissions	per household	1	€ 29	71	€ 35	87	€20	49	€25	60	€16	38	€19	48
		Total (in millions) for various aggregrat-ions	100,000												
			200,000												
			461,000	**€ 14**	**33**	**€ 16**	**40**								
			700,000					€14	34	€17	42				
			901,188									€14	34	€17	43
			1,860,000												

Average DHW fuel costs and CO2 emissions per household

DHW fuel cost and resultant CO_2 emissions at a ***household level*** corresponding with aggregation size and % of hot water load met through scheme provision at a SNSP of 75%

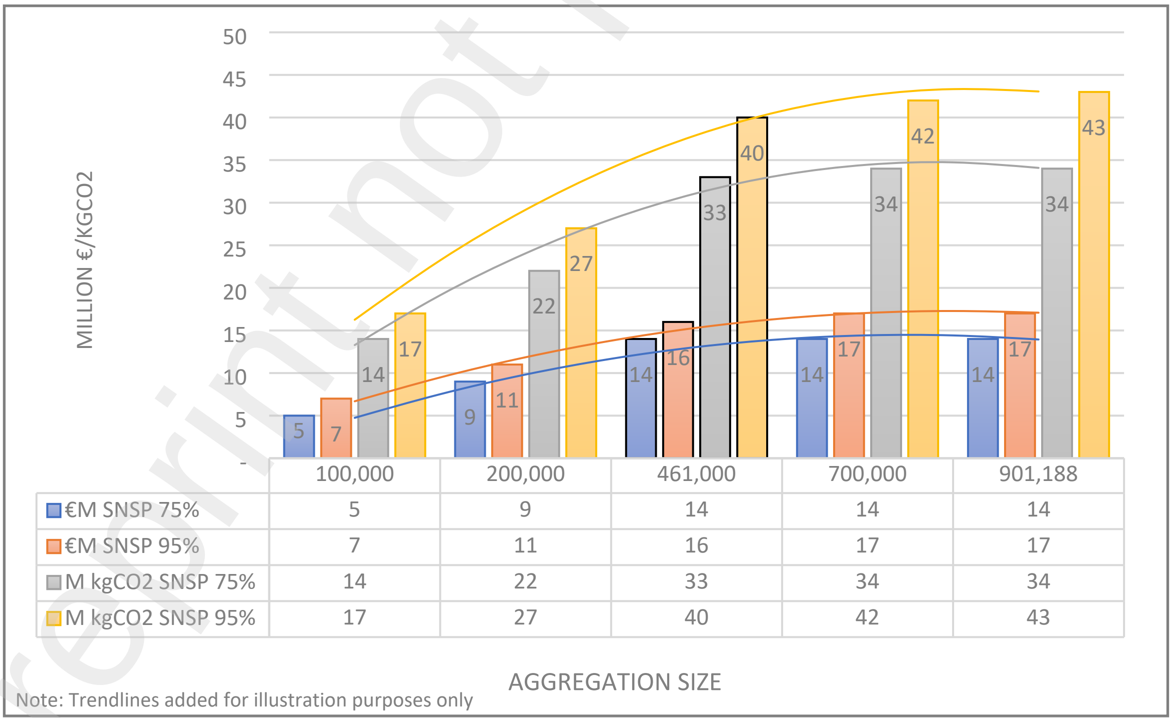


Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

While the fuel cost is typically paid for by the householder, the 'cost' of associated carbon emissions is borne by the state and the citizen. The shadow price of carbon acknowledges the cost to society that carbon emissions create in the form of climate change, air pollution, and other adverse effects sometimes called "externalities". The shadow price of carbon is a theoretical or assumed cost per metric tonne of carbon emissions used to better understand the potential impact CO_2 emissions by monetising (costing), the negative impact of environmental emissions [95, 96]. Values for the shadow price of carbon are outlined in a public spending code for Ireland [97]. According to this code, the shadow price of carbon should be based on the estimated futures price of CO_2 equivalent derived from the EU Emission Trading Scheme (EU ETS) [98]; values for produced carbon are €10 per tonne by 2020, €35 per tonne by 2030 and €100 by 2050 were recommended [96]. However, a 2019 review of carbon pricing carried out by the Irish Government found that the EU ETS failed to price carbon optimally from its perspective and consequently proposed an increase of the shadow price to €32 per tonne by 2020, €100 per tonne by 2030 and €265 by 2050 [96]; it is these shadow prices that are used to estimate the 'cost' of carbon emissions associated with average annual domestic hot water production associated with the 1.86M occupied dwellings in Ireland as €42M rising in 2022, rising to €131M in 2030 and €346M in 2050 (see Table 3). At an aggregation level of the fuel poor (461,000), and referring to data in Table 3, a potential carbon cost saving to the state of €1M in 2022 [0.033MtC0_2 x €32/tonne at 75% SNSP], rising to €4M in 2030 [0.4MtC0_2 x €100/tonne at 95% SNSP] and €10.6M in 2050 [0.4MtC0_2 x €265/tonne at 95% SNSP] might be realised through redeploying overnight curtailed wind energy to heat water in vulnerable households in Ireland.

The economics of using wind curtailment to displace energy and carbon emissions from conventionally fuelled hot water systems, assessed in Table 3, are depicted in Fig. 10 for various sample population sizes at current (75%, 2022) and future (95%, 2030) SNSP's noting that synchronous power in Ireland is typically met by gas fuelled generators with an associated emission factor of 0.2 $kgCO_2/kWh$, and at an estimated cost of €7c/kWh (based on wholesale electricity prices in Ireland in 2019 [58]).



	100,000	200,000	461,000	700,000	901,188
🟦 €M SNSP 75%	5	9	14	14	14
🟧 €M SNSP 95%	7	11	16	17	17
⬜ M kgCO2 SNSP 75%	14	22	33	34	34
🟨 M kgCO2 SNSP 95%	17	27	40	42	43

Note: Trendlines added for illustration purposes only

Fig. 10. Potential displaced cost (to Irish householder) and CO_2 emissions (in millions) from dispatch-down powered EWH for various aggregations

It is again seen that as the percentage of hot water load met decreases with increasing aggregation size (due to excess wind being a finite resource), and that the aggregated household cost and CO_2

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

savings offset through redeploying excess wind to heat hot water tails off at higher to maximum aggregations. For instance, and referring to Table 3 and Fig. 10, and at the prevailing (2023) SNSP of 75% the displaced fuel cost to the householder at an aggregation size of 100,000 households is €5M while the carbon offset is estimated at $14MtCO_2$. If the aggregation size is increased circa 5-fold, to 461,000 representing the fuel-poor population in Ireland, the displaced fuel cost rises by 280%, from €5M to €14M and the amount of carbon displaced rises by 236%, from $14MtCO_2$ to $33MtCO_2$. If the fuel poor aggregation size is roughly doubled, increasing to 901,188 dwellings, representing an additional 440,188 dwelling to the scheme and matching the amount of wind dispatched down in 2019, the displaced fuel cost would remain at €14M, while displaced carbon would rise by only 3%, from $33MtCO_2$ to $34MtCO_2$. The explanation for this is, while a larger number of tanks are being heated, they are heated less often, again because dispatch-down, as a resource, is finite. Therefore, when sustainability matchmaking, there is an optimum aggregation size wherein near maximum levels of dispatch down and carbon are offset concurrent with scheme participants receiving the maximum benefit, in this case hot water, from participating in the scheme. This is key finding of this research. Optimum aggregation size will alter depending on wind capacity, SNSP limits, and penetration of renewables into the grid. Referring to Table 1, the dispatch-down figure reduced from 1909GWh in 2020 to 752GWh in 2021, this is because 2021 was a less windy year than 2020 and SNSP limits transitioned from 65% to 75% in the same year. Notwithstanding year-to-year variations, it is important to note that dispatch-down due to energy balancing forecasted to rise significantly in line with greater penetration of wind energy targeted by Irelands ambitious climate policy [7, 13].

Finally, considering payback on the technology enabling household participation in an EWH scheme; the cost of install for the largest aggregation possible in 2019 (901,188) is estimated at €222/device resulting in a total cost of €200M that would have a simple payback of 14 years. If the fuel-poor population were aggregated (461,000) the theoretical payback would reduce to 6.4 years.

4 Discussion

It was found that while the use of domestic hot water as an energy store at scale is capable of eliminating all overnight curtailed wind energy in 2019, the value proposition in the form of 'free' hot water to the householder diminishes as more tanks are aggregated. Notwithstanding the relatively small saving to the individual householder, it is understood that those in fuel poverty limit use of hot water and therefore the receipt of a free tank of hot water weekly may be a significant boon to those who cannot afford to heat water in the first instance. Fuel poverty affects lone parents, women, people of colour and the elderly the most and can therefore be seen as a consequence of, and contributor to, injustices linked to gender, ethnicity and age. Lone parents, overwhelmingly women, and their children, are at a higher risk of fuel poverty than all other cohorts of society. It is hypothesised that the receipt of a weekly tank of hot water could become 'bath night' for these households. It is also hypothesised that there may be meta benefits arising from a provision for 'free' hot water such as positive feelings arising from inclusion in green initiatives/aggregation scheme or through relief of having one less challenge to overcome. Furthermore, it may be possible that these citizens become active actors in the energy system, this could be facilitated through push notifications sent to householders when there is a curtailment event. Such notifications could result in a change in behaviour. For example, the householder might wait to receive an alert to have a 'bath night' thereby changing behaviour to match supply of renewable energy thus allowing for greater accommodation of VRE, enhanced generation adequacy, while creating potential for deferred or avoided network investment. Such outcomes are very much in line with the ambitions of the EU 2019 Clean Energy Package of using flexibility in grid planning as an alternative to system expansion, while allowing the effective and non-discriminatory participation of residential customers. Thus, in summary, while, at larger aggregations, the monetary savings from a household perspective are not significant, cumulatively, and as shown in Fig. 10, the cost and resultant CO_2 savings to and from the residential sector-at-large are very significant. Therefore, a balance must therefore be struck between impacting

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

the quality of life for citizens in fuel poverty and the objective of reaching the furthest behind first vs the potential carbon benefit realisable by society-at-large along with the carbon cost savings realisable by the state that could be potentially diverted into energy infrastructure. To summarise, as shown in Fig. 11, the value proposition of EWH aggregation as a flexible system asset to the

- **householder or citizen** must be balanced against the value to the
- **State**, in support of meeting requirements of article 32 of the EU Clean Energy Package in enabling householders to become actors in the energy system, while creating a citizen-owned energy system that reduces the impact of fuel poverty, enabling a just transition, while reducing reliance on imported fossil fuel and resultant carbon taxes; to the
- **Climate**, through facilitating greater penetration of VRE, reducing waste and hence reduced CO_2 levels; and ultimately to the
- **Grid**, by offering *inter alia* frequency control during high wind conditions along with the creation of new markets.

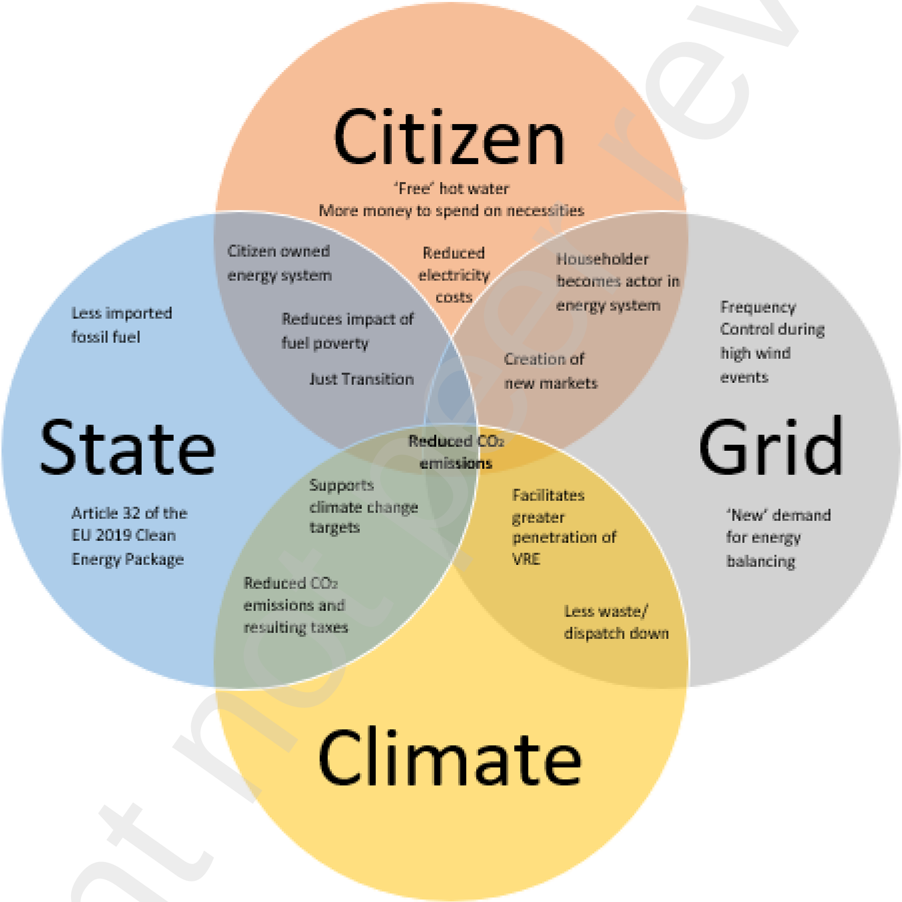


Fig. 11 Value nexus of a shared, low-cost, flexible system asset capable of eliminating wind wastage

While this study highlights the value nexus of a shared, low-cost, flexible system asset capable of eliminating wind wastage, further research is required to establish, as shown in Fig. 11, the nexus between a valuable level of demand and frequency control from say, the perspective of Ireland's TSO, to facilitate a greater penetration of VRE and an increase in SNSP limits, along with the resultant carbon that could be potentially offset at grid level, that will likely favour, as more disaggregated demand load is available, a larger aggregation, versus significantly reducing the impact of fuel poverty at a household level which this study shows to favour a smaller aggregation.

From the perspective of the 'state', favouring a 'grid' over the 'a fuel poor citizen first' approach, does not, on the face of it, support a just transition as much as taking a 'fuel poor citizen first' approach might, notwithstanding the state must balance supporting a just-transition, and reaching the furthest

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

behind first, while, as required by Article 32 of the EU 2019 clean energy package, allowing market access for all, not just fuel-poor, householders to create new markets. The state seeks also to reduce dependence on imported fossil fuel, as well as using demand flexibility to reduce investment required in energy infrastructure. It is evident thus, that more research is required to establish an optimum solution/aggregation in an Irish, but also social context.

The results of this study are in line with Agbonaye et. al., [99] who explored the value of demand flexibility for managing wind energy constraint and curtailment in Northern Ireland, finding that the optimum aggregation size and household savings varied based on whether constraint or curtailment was the primary control parameter, further making the point that there could be other competing uses for excess wind such as the production of green hydrogen for industrial use, grid-scale storage and district heating schemes. Agbonaye et. al., [17], in a different study, highlighted that households at risk of fuel poverty do not have capital to invest in heat pumps, photovoltaics and batteries etc. while electrification of heat and transport is likely to result in increased network costs, disproportionately affecting vulnerable households; concluding that it makes sense to prioritize the use of flexibility from vulnerable consumers so that they don't get left behind in the transition to clean energy. Agbonaye et. al., [19] went on to develop a methodology for identifying vulnerable neighbourhoods along with a flexibility prioritisation framework that ensures a fair distribution of flexibility opportunities.

As no country's energy provision is the same, the optimum solution will also vary country by country, for instance, in South Africa, EWH contributes up to 40% of a households total energy consumption [100], and as the households in South Africa rely almost exclusively on electricity for energy, EWH constitutes 30% to 50% of grid load at peak times, accounting for 7% of the country's daily energy requirements [33]. Since 88% of the country's electricity is generated from burning coal, the environmental water heating footprint is substantial [33]. Thus, each country needs to balance a different set of parameters to determine an optimum aggregation size for "sustainability matchmaking" [40], in other words, linking of renewable energy sources to a demand load.

Across Europe, water heating load accounted for 17% of energy consumption in households in 2012 [38]. Due to their energy storage characteristics, EWHs are considered ideal candidates for demand response [101] and it is proven that EWH aggregation schemes are useful for frequency regulation and power balancing [102-104] and thus control strategies or techniques for EWHs have received considerable academic attention in recent years [40]. Mabina et. al 2021 [40] reviewed traditional rule-based, model-based and 'model-free'/predictive machine Learning (ML) based control methods concerned with the application of demand response to control EWH, focusing particularly on studies that sought to provide ancillary grid balancing services supporting an increase in VRE in power systems. The majority of rule and model-based studies reviewed in [40] focused on controlling a single parameter, such as minimising peak load [105-112] or frequency control [62, 113-115], with one study focused on increasing the integration of wind [39]. Studies that sought to control multiple (two to three) parameters generally employed a 'model-free' ML control strategy. Multiparameter ML studies sought to control, (i) load shifting and peak load reduction [109], (ii) voltage and load reduction [116], as well as (iii) frequency regulation, load shifting and peak load reduction [117]. Mabina et. al., 2021 [40] concluded that while ML methods are faster and more accurate than model or rule-based methods, essential to load management and provision of ancillary services in the power system, none of the ML methods reviewed presented a solution that fully provided ancillary services under high penetration of renewable sources, highlighting that more research is required in this trending area, specifically;

i. ML models for energy optimization and scheduling of EWHs in a smart buildings and smart grids providing power system ancillary services,
ii. an aggregate EWH load model that can be used to analyse potential capacity reductions in a renewable grid, and

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

Preprint not peer reviewed

iii. for load-shifting models that shift EWH load from low renewable resource and high demand periods to high renewable resource and low demand periods.

In conclusion, it is interesting, to this study, that none of the EWH studies reviewed seek to maximise the benefit to the householder as a control parameter and so this area is highlighted as a topic for future research.

5 Future Research and limitations of this study

For reasons stated in section 2.2.1, wind curtailment between 7am and 10pm was excluded, future research should account for the remaining quarter (27%) of wind curtailment observed during the hours of the day not considered in this work. This will necessitate hot water use during the day to be better understood, particularly for fuel-poor households, and given that no such data exists for Irish households, and that the focus of this research is on overnight curtailed wind only, households were allocated up to 9kWh of wind curtailment, and while this is approximately the average daily hot water consumption of Irish homes, the reality is that some will require less, others more, on a given day, and others may not have a large enough cylinder to receive all of this energy at any one time. As stated previously, this broad approach will be refined;

i. when hot water consumption patterns for Irish households are published by the ESRI [79], or more ideally, as the focus is on fuel-poor dwellings specifically,
ii. on EnergyCloud pilot data, when published.

Once measured data for Irish households, ideally fuel-poor Irish households, is available, profiles can be generated using a multi-parameter methodology as defined by Ritchie et. al, 2021 [33], or with next generation machine learning methodologies proposed by Mabina et al., 2021 [40] and Bakker et al., 2008 [75] that might be used to predict, with knowledge of the expected weather and the previous day's heat profile, the water demand for the following day. Notwithstanding the model limitations, this study demonstrates that sustainability matchmaking of dispatch-down to obtain more services is worthy of greater study and that refinement of this first-round exploratory model is merited.

Understanding how hot water is consumed in fuel poor households will allow an aggregator to better understand the extent and times in which vulnerable households can benefit from and indeed *use* wind curtailment allocated to them for hot water and indeed other purposes, throughout the day, and across the year. It is important that there is need for such energy within the home and that these householders are aware of their provision before any hot water cools and their allocation is wasted – at point of use within the home rather than at the wind turbine where it is curtailed currently. It is thus important to establish if householder preferences can be accommodated within refinements to the allocation model. If householders are afforded the option to stipulate the days in which they are most likely to utilise a full allocation, then there is greater potential for the normally curtailed energy to be utilised. Similarly, it may be advantageous to ascertain if smaller allocations and/or with increased frequencies may be stipulated by householders – for example, sufficient energy for a quick shower rather than enough for a bath which may not take place. The practicalities of accommodating such preferences could be assessed within a pilot trial by way of survey or via communication platform(s) between householders, the nominated aggregator for the trial and the grid operator(s). The same platform and perhaps an in-home display will be necessary to communicate to householders that they have received an allocation of energy and that they should therefore consume their hot water before it cools.

Future research should also establish a methodology that ensures that the allocation model respects limitations of the electricity grid so that it does not constrain the network or indeed overload connections to housing estates or apartment blocks. Constraints may materialise if the roll-out of smart hot water cylinders accounts for a significant proportion of households across the state. While local networks may be overloaded if the allocation model directs too much energy in their direction.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

On the other hand, geospatial housing data could facilitate alleviation of constraints if dispatch-down is redeployed local to the constraint. It is therefore important that concurrent to the equitable distribution of energy, the allocation model accounts for the geographical spread of installations.

Further study is also recommended to establish any social or meta benefits perceived by the householder on receipt of a 'free' tank of hot water and inclusion in such a 'green' aggregation scheme.

6 Conclusion and Policy Implications

Dispatch-down has traditionally been viewed as a "bad" thing, in terms of wasted energy, this research presents a case as to how advantages can be taken of dispatch-down, an increasing resource, to obtain more services benefitting society.

This study finds that *all* of wind energy curtailed currently can be redeployed into electro-thermal hot water storage, concluding that domestic hot water cylinders offer a currently underutilised large scale, dispersed and ubiquitous micro-capacitance which can readily provide some of the needed flexibility to electrical grids, facilitating higher levels of VRE, along with ready market access for residential consumers.

It is shown in this study that redeploying all excess renewable energy, currently wasted, to heat hot water in homes, through the addition of low-cost controls on pre-existing infrastructure, had the unutilised potential to realise an averaged €256M saving to the Irish householder-at-large and to offset 633tCO_2 in 2019, realising a potential shadow carbon cost saving to the state of €6M in 2022, rising to €20M in 2030 and €162M in 2050; but while the use of domestic hot water as an energy store at scale is capable of eliminating all overnight curtailed wind energy (233GWh) in 2019, the value proposition in the form of 'free' hot water to the householder diminishes are more tanks are aggregated, indeed at the maximum scale of aggregation, households would only realise a 7% saving on their fuel bill.

A key finding of this research is that when sustainability matchmaking, there is an optimum aggregation size wherein near maximum levels of dispatch down and carbon are offset concurrent with scheme participants receiving the maximum benefit, in this case hot water, from participating in the scheme. Optimum aggregation size will alter depending on wind capacity, SNSP limits, and penetration of renewables into the grid and will therefore vary from country to country.

As this research has a focus on impacting households at risk of fuel poverty, analysis progressed to a pragmatic assessment of the extent to which a full tank of hot water can be provided for at least one night of the week so that important cleaning, bathing and hygiene tasks within each home can be catered for on a weekly basis aka 'bath night'. The benefit of which might be much more apparent to fuel poor households who are known to limit hot water use. It was found that fuel-poor households in Ireland could be provided with a 'free' full tank of hot water for 1 in every 3 weeks, capturing almost 90% of overnight curtailed wind energy in 2019 saving a theoretical €29 (10% of their bill) and €14M across the fuel-poor aggregation, realising a potential carbon cost saving to the state of €327K in 2022, rising to €1.3M in 2030 and €10.3M in 2050, simultaneously reducing the impact of fuel poverty while empowering such households in helping the state deliver on emissions and climate policy commitments.

Considering the primary infrastructure is already in place in most Irish households, and that the secondary, enabling, infrastructure is a low-cost retrofit solution. The solution proposed in this work is readily deployable and thus the significant and increasing dispatch-down resource should not continue to go unutilised. It is recommended that national policies be put in place to mandate use of

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

dispatch-down to provide new services and that in the interest of a just-transition and on reaching the furthest behind first, that fuel-poor households be aggregated to benefit initially. Due to privacy laws, it is not known publicly which houses are at risk of fuel poverty, therefore such an initiative would have need to be coordinated at government level to include the Commission for Energy Regulation, the transmission operator, distribution operators, social housing providers as well as energy suppliers and wind generators.

Future research is required to assess the potentials and economics of benefiting the fuel-poor householders to a greater or lesser degree vs benefiting society-at-large with the potential to offset a higher level of environmental emissions along with carbon cost savings, the savings of which can be potentially invested in energy infrastructure. Further research is also required to refine the wind allocation model developed in this exploratory study.

Acknowledgement: This research was partially supported by MaREI, the SFI Research Centre for Energy, Climate and Marine [Grant No: 12/RC/2303-P2].

References

[1] L. Bird, D. Lew, M. Milligan, E.M. Carlini, A. Estanqueiro, D. Flynn, E. Gomez-Lazaro, H. Holttinen, N. Menemenlis, A. Orths, P.B. Eriksen, J.C. Smith, L. Soder, P. Sorensen, A. Altiparmakis, Y. Yasuda, J. Miller, Wind and solar energy curtailment: A review of international experience, Renewable and Sustainable Energy Reviews, 65 (2016) 577-586.

[2] F.H. Permien, P. Enevoldsen, Socio-technical constraints in German wind power planning: An example of the failed interdisciplinary challenge for academia, Energy Research & Social Science, 55 (2019) 122-133.

[3] G.A.H. Laugs, R.M.J. Benders, H.C. Moll, Balancing responsibilities: Effects of growth of variable renewable energy, storage, and undue grid interaction, Energy Policy, 139 (2020) 111203.

[4] The White House, FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies, in, The White House, www.whitehouse.gov, accessed March 2021.

[5] X. Jinping, Carrying on the past and opening up a new journey of global response to climate change - Speech at the Climate Ambition Summit (December 12, 2020, Beijing), in, 2020, available from; http://www.xinhuanet.com/english/2020-12/12/c_139584803.htm, accessed March 2021.

[6] IEA Wind, IEA Wind Annual Reports 2010-2019, available from: https://iea-wind.org/, accessed March 2021.

[7] IWEA, Saving Power, 70 by 30 Implementation Plan, in, Irish Wind Energy Association, Dublin Ireland, 2020, available from: https://iea-wind.org/, accessed March 2021.

[8] P. Higgins, K. Li, J. Devlin, A.M. Foley, The significance of interconnector counter-trading in a security constrained electricity market, Energy Policy, 87 (2015) 110-124.

[9] Y. Yasuda, L. Bird, E. Maria Carlini, A. Estanquerio, D. Flynn, A. Forcione, E. Gómez Lázaro, P. Higgins, H. Holttinen, D. Lew, S. Martin-Martinez, J. McCann, N. Menemenlis, J. Charles Smith, International Comparison of Wind and Solar Curtailment Ratio, in: WIW2015 Workshop, IEA Wind, Brussels, 2015, available from; https://www.almendron.com/tribuna/wp-content/uploads/2017/06/International-Comparison-of-Wind-and-Solar-Curtailment-Ratio.pdf, accessed March 2021.

[10] Eirgrid, Annual Renewable Constraint and Curtailment Report 2019 in, Dublin, Ireland, 2020, available from; http://www.eirgridgroup.com/site-files/library/EirGrid/Annual-Renewable-Constraint-and-Curtailment-Report-2019-V1.2.pdf, accessed March 2021.

[11] Wind Europe, WindEurope views on curtailment of wind power and its links to priority dispatch, 2016, available from; https://windeurope.org/wp-content/uploads/files/policy/position-papers/WindEurope-Priority-Dispatch-and-Curtailment.pdf, accessed February 2021.

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

Preprint not peer reviewed

[12] M. Haji Bashi, L. De Tommasi, P. Lyons, Electricity market integration of utility-scale battery energy storage units in Ireland, the status and future regulatory frameworks, Journal of Energy Storage, 55 (2022) 105442.

[13] IWEA 2018, 'IWEA Energy Vision 2030 - IWEA's National Energy and Climate Plan for Ireland in 2030, available from; https://windenergyireland.com/images/files/9660bdbcf4eb198f854a95a77f61888415f034.pdf, accessed January 2021.

[14] H. Chen, J. Chen, G. Han, Q. Cui, Winding down the wind power curtailment in China: What made the difference?, Renewable and Sustainable Energy Reviews, 167 (2022) 112725.

[15] Y. Yasuda, L. Bird, E.M. Carlini, P.B. Eriksen, A. Estanqueiro, D. Flynn, D. Fraile, E. Gómez Lázaro, S. Martín-Martínez, D. Hayashi, H. Holttinen, D. Lew, J. McCam, N. Menemenlis, R. Miranda, A. Orths, J.C. Smith, E. Taibi, T.K. Vrana, C-E (curtailment – Energy share) map: An objective and quantitative measure to evaluate wind and solar curtailment, Renewable and Sustainable Energy Reviews, 160 (2022) 112212.

[16] A. Alkhalidi, K. Alqarra, M.A. Abdelkareem, A.G. Olabi, Renewable energy curtailment practices in Jordan and proposed solutions, International Journal of Thermofluids, 16 (2022) 100196.

[17] O. Agbonaye, P. Keatley, Y. Huang, O.O. Ademulegun, N. Hewitt, Mapping demand flexibility: A spatio-temporal assessment of flexibility needs, opportunities and response potential, Applied Energy, 295 (2021) 117015.

[18] S.M.G. Dumlao, K.N. Ishihara, Impact assessment of electric vehicles as curtailment mitigating mobile storage in high PV penetration grid, Energy Reports, 8 (2022) 736-744.

[19] O. Agbonaye, P. Keatley, Y. Huang, M. Bani-Mustafa, O.O. Ademulegun, N. Hewitt, Value of demand flexibility for providing ancillary services: A case for social housing in the Irish DS3 market, Utilities Policy, 67 (2020) 101130.

[20] H. Niaz, J.J. Liu, F. You, Can Texas mitigate wind and solar curtailments by leveraging bitcoin mining?, Journal of Cleaner Production, 364 (2022) 132700.

[21] T.E. Nikolakakis, T. Gutierrez, L. Fernandez, J. Kiviluoma, S. Rissanen, T.J. Lindross 2018, 'Power system flexibility for the energy transition: Part 2, IRENA FlexTool methodology', viewed October 2022.

[22] D. Dixon, EU-SysFlex Qualification Trial Process for technology Integration and trialling of System Services D4.4, in, Eirgrid, Dublin, Ireland, 2018, available from; http://eu-sysflex.com/wp-content/uploads/2019/03/D4.4-Qualification-Trial-Process-for-technology-Integration-and-trialling-of-System-Services.pdf, accessed March 2021

[23] K. Ding, J. Zhi, Chapter 6 - Wind Power Peak-Valley Regulation and Frequency Control Technology, in: N. Wang, C. Kang, D. Ren (Eds.) Large-Scale Wind Power Grid Integration, Academic Press, Oxford, 2016, pp. 211-232.

[24] M.P. Lee 2012, 'Assessment of demand response and advanced metering', viewed October 2022, <Microsoft PowerPoint - Lee.pptx (madrionline.org)>.

[25] entsoe, Market Design for Demand Side Reponse, in, Brussels, Belgium, 2015, available from; https://eepublicdownloads.entsoe.eu/clean-documents/Publications/Position%20papers%20and%20reports/entsoe_pp_dsr_web.pdf, accessed April 202222.

[26] S. Panda, S. Mohanty, P.K. Rout, B.K. Sahu, M. Bajaj, H.M. Zawbaa, S. Kamel, Residential Demand Side Management model, optimization and future perspective: A review, Energy Reports, 8 (2022) 3727-3766.

[27] R. Bloom, L. Sugden, Status and opportunities for flexible residential E-HVAC, DELTA-EE, Edinburgh, Scotland, 2021, available from; www.delta-ee.com, accessed March 2021.

[28] European Commission 2018, *Realising Value from Electricity Markets with local smart electric thermal storage technology*, EU Commission, viewed October 2022, https://cordis.europa.eu/article/id/241249-smart-storage-heaters-benefit-households-and-business, accessed April '22.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

[29] A. Bloess, W.-P. Schill, A. Zerrahn, Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials, Applied Energy, 212 (2018) 1611-1626.

[30] B.B. Andrade, P.N. Rathie, Fitting asymmetric bimodal data with selected distributions, Journal of Statistical Computation and Simulation, 86 (16) (2016) 3205-3224.

[31] C. Ahern, P. Griffiths, M. O'Flaherty, State of the Irish Housing stock - Modelling the heat losses of Ireland's existing detached rural housing stock & estimating the benefit of thermal retrofit measures on this stock, Energy Policy, 55 (2013) 139-151.

[32] EirGrid 2016-2018, *Power off and save*, EirGrid, viewed February 2021, <http://www.eirgridgroup.com/how-the-grid-works/power-off-save/>, accessed May 2022.

[33] M.J. Ritchie, J.A.A. Engelbrecht, M.J. Booysen, A probabilistic hot water usage model and simulator for use in residential energy management, Energy and Buildings, 235 (2021) 110727.

[34] P. Fairey, D. Parker, A review of hot water draw profiles used in performance analysis of residential domestic hot water systems, in, Florida Solar Energy Center/University of Central Florida, Florida, US, 2004.

[35] M. Roux, M.J. Booysen, Use of smart grid technology to compare regions and days of the week in household water heating, in: 2017 International Conference on the Domestic Use of Energy (DUE), 2017, pp. 276-283.

[36] M.W. Jack, K. Suomalainen, J.J.W. Dew, D. Eyers, A minimal simulation of the electricity demand of a domestic hot water cylinder for smart control, Applied Energy, 211 (2018) 104-112.

[37] P. Kepplinger, G. Huber, J. Petrasch, Field testing of demand side management via autonomous optimal control of a domestic hot water heater, Energy and Buildings, 127 (2016) 730-735.

[38] P. Kepplinger, G. Huber, M. Preißinger, J. Petrasch, State estimation of resistive domestic hot water heaters in arbitrary operation modes for demand side management, Thermal Science and Engineering Progress, 9 (2019) 94-109.

[39] L. Gelažanskas, K. Gamage, Distributed Energy Storage Using Residential Hot Water Heaters, Energies, 9 (3), 127 (2016).

[40] P. Mabina, P. Mukoma, M.J. Booysen, Sustainability matchmaking: Linking renewable sources to electric water heating through machine learning, Energy and Buildings, 246 (2021) 111085.

[41] J. Slowe, Hot Water tanks get smarter, in, Edinburgh, Scotland, 2020, www.delta-ee.com, Accessed March 2021.

[42] H. Hao, B.M. Sanandaji, K. Poolla, T.L. Vincent, Potentials and economics of residential thermal loads providing regulation reserve, Energy Policy, 79 (2015) 115-126.

[43] N. Lu, An evaluation of the HVAC load potential for providing load balancing service, IEEE Transactions on Smart Grid, 3 (3) (2012) 1263-1270.

[44] J.L. Mathieu, S. Koch, D.S. Callaway, State estimation and control of electric loads to manage real-time energy imbalance, IEEE Transactions on Power Systems, 1 (2013) 430-440.

[45] S. Kundu, N. Sinitsyn, S. Backhaus, I. Hiskens, Modeling and control of thermostatically controlled loads, arXiv preprint arXiv:1101.2157, (2011).

[46] W. Zhang, J. Lian, C.Y. Chang, K. Kalsi, Aggregated modeling and control of air conditioning loads for demand response, IEEE Transactions on Power Systems, 28 (4) (2013) 4655-4664.

[47] S. Bashash, H.K. Fathy, Modeling and control of aggregate air conditioning loads for robust renewable power management, IEEE Transactions on Control Systems Technology, 21 (4) (2013) 1318-1327.

[48] X. Epiard, B. Prestat, EDF experience with storage in EU and US markets, in: World Future Energy

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

Summit, www.issuu.com, Abu Dhabi, UAE, 2017

[49] K. Marnell, C. Eustis, R.B. Bass, Resource study of large-scale electric waterheater aggregation, IEEE Open Access Journal of Power and Energy, 7 (2020) 82-90.

[50] Government of Oregaon, Actively adapting to the changing electricity sector, 2018, available from; https://www.oregon.gov/puc/utilities/Documents/SB978LegislativeReport-ExecSummary.pdf, accessed April 2021 [36]

[51] EirGrid (Ireland), SONI (Northern Ireland) 2020, 'Balancing Market Principles Statement - A Guide to Scheduling and Dispatch in the Single Electricity Market', viewed June 2021, <https://www.eirgridgroup.com/site-files/library/EirGrid/EirGrid-and-SONI-Balancing-Market-Principles-Statement-V4-0-(final).pdf>.

[52] EN 50440, Efficiency of domestic electrical storage water heaters and testing methods, in, European Standard, 2015.

[53] M.A. López-Rodríguez, I. Santiago, D. Trillo-Montero, J. Torriti, A. Moreno-Munoz, Analysis and modeling of active occupancy of the residential sector in Spain: An indicator of residential electricity consumption, Energy Policy, 62 (2013) 742-751.

[54] M.J. Booysen, M. Visser, R. Burger, Temporal case study of household behavioural response to Cape Town's "Day Zero" using smart meter data, Water Research, 149 (2019) 414-420.

[55] O. Gerin, B. Bleys, K. de Cuyper 2014, 'Seasonal variation of hot and cold water consumption in apartment buildings', viewed January '23, < https://www.irbnet.de/daten/iconda/CIB_DC27564.pdf>.

[56] S. Gato, N. Jayasuriya, P. Roberts, Forecasting Residential Water Demand: Case Study, Journal of Water Resources Planning and Management, 133 (4) (2007) 309-319.

[57] S.L. Zhou, T.A. McMahon, A. Walton, J. Lewis, Forecasting operational demand for an urban water supply zone, Journal of Hydrology, 259 (1) (2002) 189-202.

[58] J. de Santiago, O. Rodriguez-Villalón, B. Sicre, The generation of domestic hot water load profiles in Swiss residential buildings through statistical predictions, Energy and Buildings, 141 (2017) 341-348.

[59] D. George, Mech 6340 Project High time-step resolution measured domestic hot water consumption profiles of single detached Canadian homes, Dalhousie University, February, 13 (2015).

[60] E.J.M. Blokker, J.H.G. Vreeburg, J.C. van Dijk, Simulating Residential Water Demand with a Stochastic End-Use Model, Journal of Water Resources Planning and Management, 136 (1) (2010) 19-26.

[61] J. Sborz, A. Kalbusch, E. Henning 2022, 'A Review on Domestic Hot Water Consumption in Social Housing', *Water*, vol. 14, no. 17, DOI 10.3390/w14172699.

[62] R. Diao, S. Lu, M. Elizondo, E. Mayhorn, Y. Zhang, N. Samaan, Electric water heater modeling and control strategies for demand response, in: 2012 IEEE Power and Energy Society General Meeting, 2012, pp. 1-8.

[63] Energy Savings Trust, Measurement of Domestic Hot Water Consumption in Dwellings, in, 2008. Available from; https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48188/3147-measure-domestic-hot-water-consump.pdf, viewed January '23

[64] U. Jordan, K. Vajen, DHWcalc: Program to generate domestic hot water profiles with statistical means for user defined conditions, in.ISES Solar world congress, Orlando (US), 8 (2005)

[65] D. Fischer, T.R. Toral, K.B. Lindberg, B. Wille-Haussmann, H. Madani, Investigation of Thermal Storage Operation Strategies with Heat Pumps in German Multi Family Houses, Energy Procedia, 58 (0) (2014) 137-144.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

[66] A. Ferrantelli, K. Ahmed, P. Pylsy, J. Kurnitski, Analytical modelling and prediction formulas for domestic hot water consumption in residential Finnish apartments, Energy and Buildings, 143 (2017) 53-60.

[67] J. Widén, M. Lundh, I. Vassileva, E. Dahlquist, K. Ellegård, E. Wäckelgård, Constructing load profiles for household electricity and hot water from time-use data—Modelling approach and validation, Energy and Buildings, 41 (7) (2009) 753-768.

[68] D. Popescu, E. Serban, Simulation of domestic hot-water consumption using time-series models, Proceedings of the 6th IASME/WSEAS International Conference On Heat Transfer, Thermal Engineering and Environment, (2008) 20-22.

[69] D. Marini, R. Buswell, C. Hopfe, A critical software review-how is hot water modelled in current building simulation?, (2015).

[70] A. Gholizadeh, V. Aravinthan, Benefit assessment of water-heater management on residential demand response: An event driven approach, in, IEEE, pp. 1-6.

[71] S. Edwards, I. Beausoleil-Morrison, A. Laperrière, Representative hot water draw profiles at high temporal resolution for simulating the performance of solar thermal systems, Solar Energy, 111 (2015) 43-52.

[72] S.G. Buchberger, G.J. Wells, Intensity, duration, and frequency of residential water demands, Journal of Water Resources Planning and Management, 122 (1) (1996) 11-19.

[73] M. Richard, Simulating domestic hot water demand by means of a stochastic end-use model, Thesis (MEng)--Stellenbosch University, (2016).

[74] N.D. Pflugradt, Modellierung von wasser und energieverbräuchen in haushalten, (2016). Dissertation Technical universitat Chemnitz, Germany.

[75] V. Bakker, A. Molderink, J.L. Hurink, G.J.M. Smit, Domestic Heat Demand Prediction Using Neural Networks, in: 2008 19th International Conference on Systems Engineering, 2008, pp. 189-194.

[76] O. Neu, S. Oxizidis, D. Flynn, D. Finn, Utilising time of use surveys to predict domestic hot water consumption and heat demand profiles of residential building stocks, British Journal of Environment and Climate Change, 6 (2) (2016) 77-89.

[77] R. Matlab, Statistics toolbox release, Natick: The MathWorks Inc, (2012).

[78] SAP, The (UK) Government's Standard Assessment Procedure for Energy rating of Dwellings, in: DEFRA (Ed.), Published on behalf of DEFRA by: Building Research Establishment, Garston, Watford, 2005.

[79] ESRI 2023, *Efficiency of Houshold Hot Water Use*, viewed January 2023, <https://www.esri.ie/current-research/efficiency-of-household-hot-water-use>, accessed January 2023

[80] SEAI, Energy in the Residential Sector - 2018 Report, 2018, available from; https://www.seai.ie/publications/Energy-in-the-Residential-Sector-2018-Final.pdf, accessed April 2021.

[81] Kingspan, Kingspan Hot Water Cylinders Product Guide, available from; https://www.kingspan.com/gb/en-gb/products/hot-water-cylinders/resources, accessed October 2021

[82] climote *climote*, viewed February 2023, <https://www.climote.ie/>.

[83] S. Kamal, Energy Follow Up Survey: Fuel Poverty, in, 2018., available from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1018737/efus-fuel-poverty.pdf, access January 2023

[84] SEAI 2023, *Average electricity price to households*, viewed January 2023, <https://www.seai.ie/data-and-insights/seai-statistics/key-statistics/prices/>.

[85] A. Sawyer, N. Sherriff, D. Bishop, M. Darking, J.W. Huber, "It's changed my life not to have the continual worry of being warm" – health and wellbeing impacts of a local fuel poverty programme: a mixed-methods evaluation, BMC Public Health, 22 (1) (2022) 786.

[86] C. O'Doherty, Families live in constant cold as energy poverty forces heat rationing, in: The Irish Independent, Independent New and Media, Dublin Ireland, 2021.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

[87] EnergyCloud 2023, *Innovative solutions to divert otherwise wasted renewable erngy to Irish homes in fuel poverty*, www.energycould.org, viewed January 2023.

[88] Eirgrid 2023, *Smart Grid Dashboard*, viewed January 2023, <https://www.smartgriddashboard.com/#all>.

[89] D. Roddy, Energy Cloud, in: B. Moorhead (Ed.) The Grid - The Energy Transition, eSmart Networks, Northern Ireland, 2023.

[90] Element Energy, Bottom-up analysis of fuel poverty in Ireland, in, 2015, avaialble from https://assets.gov.ie/76593/331e2543-a5a1-4057-a902-d0e2a8827d50.pdf, access March 2022

[91] R. Nestor, Social Impact Assessment - SEAI Programmes Targeting Energy Povery, in: Department of Public Expenditure and Reform (Ed.), Irish Government Economic and Evaluation Service, Dublin Ireland, 2020.

[92] CSO 2019, *Survey on Income and Living Conditions (SILC) 2019*, CSO, viewed 29th March 2021.

[93] CSO, Profile 1: Housing in Ireland, in: Central Statistics Office of Ireland (Ed.), Cork, Ireland, 2016 https://www.cso.ie/en/csolatestnews/presspages/2017/census2016profile1-housinginireland/, viewed 29th March 2021..

[94] CSO 2022, *Census of Population - Preliminary Results*, Central Statistics Office, viewed September 2022 2022, <https://www.cso.ie/en/releasesandpublications/ep/p-cpr/censusofpopulation2022-preliminaryresults/housing/#:~:text=A%20total%20of%202%2C124%2C590%20permanent,(%2D9%25)%20to%20166%2C752.>.

[95] Gold Standard 2021, Carbon Pricing: Setting an internal price on carbon; available from; https://www.goldstandard.org/blog-item/carbon-pricing-setting-internal-price-carbon, accessed January 2021.

[96] Government of Ireland, An Overview of Carbon Pricing, in: Parliamentary Budget Office (Ed.), Houses of the Oireachtas, Dublin Ireland, 2019; available from https://data.oireachtas.ie/ie/oireachtas/parliamentaryBudgetOffice/2019/2019-07-04_an-overview-of-carbon-pricing_en.pdf, accessed January 2021.

[97] Government of Ireland, Public Spending Code A Guide to Economic Appraisal: Carrying Out a Cost Benefit Analysis, in: Public Spending Code, A Guide to Evaluating, Planning and Managing, Public Investment (Eds.), Government of Ireland, Dublin, Ireland, 2019; available from; https://www.gov.ie/en/publication/public-spending-code/, accessed January 2021.

[98] European Commission 2005, EU Emissions Trading System (EU ETS), available from; https://ec.europa.eu/clima/policies/ets_en, accessed January 2021.

[99] O. Agbonaye, P. Keatley, Y. Huang, F.O. Odiase, N. Hewitt, Value of demand flexibility for managing wind energy constraint and curtailment, Renewable Energy, 190 (2022) 487-500.

[100] P.A. Hohne, K. Kusakana, B.P. Numbi, A review of water heating technologies: An application to the South African context, Energy Reports, 5 (2019) 1-19.

[101] A. Arteconi, N.J. Hewitt, F. Polonara, State of the art of thermal storage for demand-side management, Applied Energy, 93 (2012) 371-389.

[102] Elamari et al., Using electric water heaters (EWHs) for power balancing and frequency control in PV-Diesel Hybrid mini-grids, World Renewable Energy Congress, Sweden (2011), 57:13, pp 842-850

[103] D. Cooper, W. Cronje, Autonomous water heater control for load regulation on smart grids, in, 2016 IEEE Internal Energy Conference, Belgium, pp. 1-6.

[104] Z. Xu, R. Diao, S. Lu, J. Lian, Y. Zhang, Modeling of electric water heaters for demand response: A baseline PDE model, IEEE Transactions on Smart Grid, 5 (5) (2014) 2203-2210.

[105] J.C. Laurent, G. Desaulniers, R.P. Malhamé, F. Soumis, A column generation method for optimal load management via control of electric water heaters, IEEE Transactions on Power Systems, 10 (3) (1995) 1389-1400.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515

[106] A. Sepulveda, L. Paull, W.G. Morsi, H. Li, C.P. Diduch, L. Chang, A novel demand side management program using water heaters and particle swarm optimization, in, 2010 IEEE Electrical Power and Energy Conference, Canada, pp. 1-5.

[107] P. Kepplinger, G. Huber, J. Petrasch, Demand side management via autonomous control-optimization and unidirectional communication with application to resistive hot water heaters, ENOVA: Eisenstadt, Austria, 8 (2014).

[108] E.C. Kara, M. Berges, B. Krogh, S. Kar, Using smart devices for system-level management and control in the smart grid: A reinforcement learning framework, in, 2012 IEEE Third International Conference on Smart Grid Communications, Taiwan, (2012), pp. 85-90.

[109] C. Diduch, M. Shaad, R. Errouissi, M.E. Kaye, J. Meng, L. Chang, Aggregated domestic electric water heater control-building on smart grid infrastructure, in, IEEE, pp. 128-135.

[110] K. Al-Jabery, D.C. Wunsch, J. Xiong, Y. Shi, A novel grid load management technique using electric water heaters and Q-learning, in, IEEE innovative Smart Grid Technologies, (2017), pp. 776-781.

[111] Y. Guo, N. Mahdavi, Machine learning method for day classification to understand thermostatically controlled load demand, in, IEEE, pp. 1-5.

[112] N. Lu, S. Katipamula, Control strategies of thermostatically controlled appliances in a competitive electricity market, in, IEEE Power Engineering Society General Meeting, (2005) pp. 202-207.

[113] M. Liu, Y. Shi, Model predictive control of aggregated heterogeneous second-order thermostatically controlled loads for ancillary services, IEEE transactions on power systems, 31 (3) (2015) 1963-1971.

[114] Y. Zong, G.M. Böning, R.M. Santos, S. You, J. Hu, X. Han, Challenges of implementing economic model predictive control strategy for buildings interacting with smart energy systems, Applied Thermal Engineering, 114 (2017) 1476-1486.

[115] Z. Qu, C. Xu, K. Ma, Z. Jiao, Fuzzy neural network control of thermostatically controlled loads for demand-side frequency regulation, Energies, 12 (13) (2019) 2463.

[116] M.H. Nehrir, R. Jia, D.A. Pierre, D.J. Hammerstrom, Power management of aggregate electric water heater loads by voltage control, in, IEEE, pp. 1-6.

[117] J. Kondoh, N. Lu, D.J. Hammerstrom, An evaluation of the water heater load potential for providing regulation service, in, IEEE, 23 (3) (2010), pp. 1-8.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4566515