The potential of power-to-heat demand response to improve the flexibility of the energy system: An empirical review

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ABSTRACT

This paper provides a systematic review of 34 large-scale projects of power-to-heat demand response. The projects have been classified in terms of location, size, technical implementation and objective. The chronological ordering of the reviewed projects enables key takeaways to be drawn considering other developments in the energy sector, such as its restructuring and the emergence of competing flexibility options. The presented approach provides renewed insight to the debate on power-to-heat demand response diffusion. Historically, power-to-heat demand response has been used because of its wide availability on the demand side. Within utility programs, it has mostly been used to deal with infrastructure capacity limitations. This is still a major driver for power-to-heat demand response today. To address the challenges that come with the integration of renewable energy sources, more recent research projects have focused on exploring its capability to provide real-time balancing and frequency response at a smaller scale. The literature review suggests that the period of energy sector restructuring introduced uncertainty to energy companies regarding power-to-heat demand response and thus influenced its use. This period is now superseded by developments focused on electricity markets that are open to the demand side. Considering the flexibility requirement of the future energy system, new opportunities arise for power-to-heat demand response. Based on a critical analysis of the technical and regulatory changes, this paper makes the claim that the economic and policy frameworks have had a much more significant effect on the varying diffusion of power-to-heat demand response than the effect of the control and information technologies. In that sense, market rules should be carefully tailored so as to unlock the flexibility not only of power-to-heat demand response, but also of other flexibility resources.

HIGHLIGHTS

- P2H DR has multiple capabilities suitable for different time scales
- Technical feasibility of P2H DR is not a significant barrier
- Framework uncertainty has a significant effect on P2H DR diffusion

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- Markets and flexibility requirement introduce new option for P2H DR

KEYWORDS

Ancillary services, electricity markets, frequency response, flexibility, projects, smart energy systems.

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LIST OF ABBREVIATIONS

AC	Air conditioner
AMI	Advanced monitoring infrastructure
CHP	Combined heat and power plants
CPP	Critical peak pricing
DLC	Direct load control
DR	Demand response
DSM	Demand side management
DSO	Distribution system operator
DH	District heating
DHC	District heating and cooling
EWH	Electric water heater
EU	European Union
EV	Electric vehicle
GHG	Greenhouse gas
HAN	Home area network
HVAC	Heating, ventilation and air conditioning
HAMS	Home automation management system
HP	Heat pumps
ICT	Information and communication technologies
IEEE	Institute of Electrical and Electronics Engineers
LV	Low voltage
LAN	Local area network
NAN	Neighborhood area network
PV	Photovoltaic
PLC	Power line communication
P2H	Power-to-heat
RES	Renewable energy sources
RTP	Real time pricing
RTT	Real time trading
TCL	Thermostatically controlled loads
TOU	Time-of-use
TSO	Transmission system operator
UK	United Kingdom
US	United States
VHF	Very high frequency
WAN	Wide area network
4GDH	Fourth generation district heating

1. INTRODUCTION

History shows that the energy transition has, more often than not, been a slow process marked by few noteworthy technological leaps and periods of their incremental diffusion. These leaps are traced back to scientific inquiry and quest for greater conversion efficiency, convenience and lower cost. Under significant climate concerns, however, today's fossil based energy system is facing more rapid transformations [1]. The diffusion of renewable energy sources (RES) and information and communication technologies (ICT) is changing the way the energy system is being operated.

Substituting synchronous generation for variable, inverter-coupled energy sources raises a number of issues related to reduced system inertia [2], controllability [3] and resilience [4]. In this context, improving energy system flexibility is seen as a key enabler of energy systems with high renewable penetration [5]. As noted in [6], there is no one-size-fits-all solution to achieve a sustainable energy system. Rather, the transition should be approached systematically, having in mind all of the possible technologies and approaches. The comprehensive overview of [6] lists, among others, demand side management, storage, infrastructure investments, market mechanisms and ancillary services as some of the necessary tools for improving the energy system flexibility [7]. Integrating the urban and energy planning can additionally facilitate the reduction of GHG emissions and improve energy savings [8].

Hence, the energy sector becomes a system of systems that are technically and administratively intertwined. After removing this layer of abstraction, one is able to see how this grand machinery-like concept is simply comprised of many constituent parts that are both technically viable and already present in the field. A plethora of pilot and utility scale projects are already underway hoping to enhance the understanding of these synergies. They focus on thermal energy storage [9] and demand side flexibility [10], battery storage [11], district heating and cooling (DHC) [12], demand response (DR) in Europe [13], China [14] or internationally [15], vehicle-to-grid [16], smart grid projects in Europe [17] and Brazil [18], power-to-gas [19], alternative fuels [20] etc.

This paper focuses on power-to-heat (P2H) DR as a specific field of research found at the intersect of demand side management and energy sector coupling. It has raised significant interest in the research community due to the variety of technologies which can be used and their presence on the demand side. The distinct capabilities of P2H DR have been debated in previous research as well, both from a theoretical [21] and a practical aspect, with a focus on projects from 2010-2016 [9] or as part of general international DR experiences [15]. A survey with a broader time horizon than [9] and a more specific focus than [15] could provide a better comprehension of the potential of P2H DR.

This paper contributes to the debate by analyzing P2H DR large-scale projects from an empirical point of view, with a broadened survey in terms of time horizon and geography, thus building on works such as [9] and [15]. The review provides clear evidence on the technical potential, the scale, the type of implementation, the goal of the DR action and the environment in which P2H DR has been applied most successfully. By exploring different projects as they evolve over time, the analysis provides a new outlook on the enablers and barriers of P2H deployment for improving the energy system flexibility. With the aim of being objective, there is no demand for evidence on P2H DR being a solution to all challenges. Instead, the review explores the role of P2H DR in the context of the new challenges of the energy system, drawing from quantitative results and an interpretive critical discussion on the effects of the market liberalization and the emergence of new technologies.

2. METHODS

The literature review has been conducted so as to address the research question "*Is power-to-heat demand response mature enough to be deployed on a mass scale with the aim of improving the flexibility of the energy system?"*. The presented research question is similar to that of [9], but is relaxed in that it does not mention the requirement for P2H DR to provide a "*key contribution*", as the term "*key contribution*" in non-definite. In order to address the maturity of P2H demand response, this paper reviews the empirical evidence of field projects and scientific works related to incentive-based (direct) and price-based (indirect) DR [22]. A DR action from P2H is considered to be mature given that it demonstrates technical potential for flexibility provision, taking into account past field experience.

The literature has been selected by a chronological review of publications, programmes and projects dealing with *demand response* and *demand side management* (DSM) related to *thermal storage*, *electric water heaters* (EWH), *air conditioners* (ACs), *HVAC, thermostatically controlled loads* (*TCL*) and *heat pumps* (HP). Online databases of relevant journals (Renewable and Sustainable Energy Reviews, Applied Energy, Energy, Energy Policy, Renewable Energy, IEEEXplore) were considered as a starting point of the review and the keywords noted above were tracked since the first published issue which was available online in these journals/databases. This core body of literature was systematically supplemented with works which have been consecutively developed upon them. To ensure that the review process was as complete as possible, additional references were collected through search engines such as Mendeley and Google Scholar.

Based on the reviewed literature, the deployment of P2H DR has been studied as a function of the influencing technical, economic, and political factors, as well as their evolution throughout time and within different regions. Since many of these factors are difficult to quantify, a statistical approach is not deemed suitable. Instead, an interpretive analysis of the historical discourse has been adopted. This permits evidence to be drawn in a contextual manner, by providing links between the success of certain approaches and the framework conditions in which they have been deployed. These links need to be based on a clear set of questions which arise from the review. Drawing from [9], the projects have been classified in terms of location, size, technical implementation and objective. To assess the posed research question, the argumentation is developed along the findings related to (i) the technical capabilities of P2H DR, (ii) the evolution of the ICT infrastructure and (iii) the changes in the framework conditions. A critical discussion and an outlook for possible future research is given on the basis of this argumentation.

3. HISTORICAL DEVELOPMENT

This section presents a systematic review of the large scale projects dealing with P2H DR. The projects have been ordered chronologically and separated into four periods, based on the year of implementation or on the year that they have been reported.

2.1 Until 1950s

The earliest attempts to unlock the flexibility potential of the demand side were based on indirect DR actions, such as time-of-use (TOU) tariffs [23]. Dating back to 1895, TOU tariffs are the oldest form of DR found in the literature and they were used to increase profits by encouraging daytime load [24]. In 1956 the requirement of the French power system to flatten the load curve motivated Electricite de France (EDF) to introduce three different prices in winter days for the 150,000 largest industrial consumers.

The first direct DR actions, on the other hand, depended on ripple control as an enabling communication technology. Ripple control is based on a one-way communication system with a transmitter and receiver units. The control is achieved by modifying the primary waveform of 50 Hz or 60 Hz by overlaying signals of higher frequency (200 Hz to 1000 Hz). Appliances are thus turned on or off when the receivers installed at the demand side receive these signals. The technology dates back to the beginning of the 20th century and finds early adoption in Paris in 1928 for the control of public lighting [22]. It is reported to have been used in Germany in the 1930s for direct load control, although the scale of the controlled load at that time is unknown [25]. Outside of Europe, since the 1950's, ripple control has enabled distribution companies in New Zealand to reduce peak demand by turning EWHs off [26].

2.2 During 1960s-1980s

The demand side coupling of the power and heat sectors continued throughout the 1960s and up to 1980s with larger utility scale projects [27]. A systematic classification of the most notable project is given in Table 1. The year noted in the tables indicates when the project was initiated or first reported in the literature. To understand P2H DR, one can trace its origins to the first general classifications of DR as a demand side measure. Among the pioneers in the field, Gellings defined DSM as an umbrella term for all measures related to load management, new uses, strategic conversion, electrification, costumer generation and adjustment of market share [27]. Similar definitions of DSM's scope can later be found in more contemporary works, such as that of Palensky and Dietrich [28]. Later [22] deals with the terms DSM, DR and load management without strict distinctions. The first glossary of terms was developed by the Terminology Task Force of the Load Management Subcommittee [29]. But despite being a first iteration, the systematic approach of these papers has laid out the groundwork for much of DSM, as it is known today. Research at that time was developed in areas such as probabilistic [30] and stochastic [31] models, as well as in design of air-conditioning and storage systems that would enable load shifting [32]. Soon, it became evident that DSM stands in the face of wide horizons [23]. To be aware of all the DSM alternatives and to be able to evaluate the best for a given application were often the issues raised [33]. For this purpose, the Institute of Electrical and Electronics Engineers (IEEE) Load Management Subcommittee developed a generic classification of DSM alternatives. This rather disaggregated ordering is provided in [34] along with a cross reference matrix showing the many other ways that DSM alternatives can be classified. For instance, DSM alternatives can be classified in terms of the degree of end user/utility involvement, the consumer type, the communication mode, the type of load modification, the party exercising control, the type of tariff etc.

The most notable early experiences with large-scale projects of P2H DR are found in the US. Ripple control has been used in Michigan as early as 1968 [35]. The ten-year experience in Michigan showed that demand side programmes must be carefully initiated by taking into account other flexibility alternatives. This can help avoid making unnecessary investments, or as stated in [35]: "*Since all energy storage devices act to trim peaks and fill load valleys, energy storage and Load Management are competitors*". In order to lower peak demand, utility level projects at the time also focused on promoting storage space heating and remote control cycling of electric water heaters [36]. On average, households were given around $25-30, should they participate in DR programmes that enabled utilities to cycle their air conditioners and water heaters as needed [37]. The programme of Florida Power Corporation showed that consumers were willing to provide more control over their air conditioners and electric water heaters for a larger financial reimbursement. Hence, 80% of consumers preferred being given $8.00 per month to participate in a programme with a 50% cycling strategy, while only 20% of consumers preferred being given $2.00 per month for a 25% cycling programme [38]. Another P2H DR field project in Florida has been discussed in [39]. Experiences of similar projects showed average per household load reduction of 1 kW for air conditioners and 0.6 – 1 kW for EWH. By the 1980s's experience with P2H DR had been steadily growing in the US [38]. About 52,500 participants with more than 100,000 appliances (EWH, AC, HVAC and pool pumps) had been participating in Florida Power's DR programme by 1981. A few years later, the programme grew to about 490,000 participants enabling a 10% peak reduction (712 MW peak reduction during a 6892 MW demand) [40].

As noted in [37], "*DSM efforts outside of North America have been limited*" in this period. However, time switches have been used along with storage space heaters to flatten the demand curve in the UK [13]. This measure was complementary to the nuclear power programme of the UK at the time. Time switches were slowly replaced by direct ripple control. In the 1960s, ripple control and TOU tariffs were introduced by a few Swedish distribution system operators, although at a smaller pilot scale [25]. Around this time, ripple control is also found in other countries in Europe, Japan and Australia [22]. Meanwhile, the European experience with price based DR is notable in France. The vertically integrated utility in France, EDF France, had then aggregated around 880 MW. Hence, a 1.5% peak reduction was achieved in 1985, just three years into the DR programme [41]. Along with France, other European countries had implemented some sort of indirect (price-based) DR, although not specifically designed for P2H.

Table 1. Review of P2H DR projects up to 1980s

Project	Year	Location	Size	Technology	Communication	Objective	Implementation	Takeaway
Transpower [22]	1950-	New Zealand	N.A.	EWH	PLC, ripple control	Peak clipping	Load curtailment	Among the first DR programmes Demand Response Management System (DRMS) purchased to scale programme
UK distribution companies [13]	1960s	UK	N.A.	Thermal storage heaters	Radio and tele-switched meters	Load factor improvement	Time-controller	Complement to the UK nuclear power plant programme
Detroit Edison Company, Michigan [35]	1968	US	200,000	EWH	Manual on-site control, substituted by radio ripple control	Peak clipping	On/off cycling	-Approximated water heater demand 200 MW - Reliability of communication infrastructure issues

Table 1. Review of P2H DR projects up to 1980s (contd.)

Project	Year	Location	Size	Technology	Communication	Objective	Implementation	Takeaway
Florida Power Corporation [38,40]	1981	US	Up to 1981 52,500 participants: 50,000 EWH, 45,000 ACs, 42,000 central heating systems, 8,000 pool pumps, 35,000 commercial space conditioning equipment. In 1988: 490,000 participants	EWH, AC, HVAC, pool pumps	Radio ripple control, VHF radio	Peak clipping	On/off cycling	- 712 MW peak reduction (6892 MW peak) - Consumer acceptance: 30-46.3% - Hardware and communication reliability: > 97% - Load shaping depends on time, temperature and control strategy
EDF France [41]	1985	France, EU	- 25,000,000 LV consumers - 7,000,000 LV consumers with TOU tariff	EWH, HP, arc furnaces etc.	PLC, ripple control, time switches	Peak clipping	Load curtailment	- 1.5% peak reduction - 3,700,000 with LV consumers with TOU tariffs and time switches, 3,300,000 with ripple control
Florida Power and Light [39]	1988	US	510,000 DLC participants, 152,000 TOU participants	AC, EWH, HP, pool pumps	PLC, telephone lines	- Maximize user flexibility - Peak clipping	- On/off cycling - Load curtailment	- User friendly man-machine interface and load control algorithm were developed

2.3 During 1990s-2010

As shows in Table 2, P2H DR programmes had a clearly demonstrated potential in reducing peak demand by the 1990s [40]. The Sacramento Municipal Utility District Residential Peak Corps aggregated 19,130 participants with central air conditioning loads and achieved a 100 MW peak reduction (4.66% of the 2145 MW peak load). Similarly, the United Power Association Off Peak programme achieved a 92 MW peak reduction (14.22% of the 647 MW peak load). It consisted of storage space heater, electric water heaters, air conditioning units and irrigation pumps. The Buckeye Power Residential Load Control programme focused on electric water heaters and space heaters. Although it did not provide special incentives to consumers, it aggregated 81 MW, but achieved only 14 MW peak reduction (1.46% of the 956 MW peak load) [40]. Learning from past experience of other utilities, new initiative arose. For example, Houston Lighting & Power had 20,000 new installations in 1993 and, with intense marketing, aimed at 100,000 by the year 2000 [42]. Their experience, similar to that of others, showed that residential P2H DR capacity averages around 1 kW per participant. All of the above mentioned project are based on VHF radio signals to be transmitted to end-consumers whose heating/cooling devices were controlled.

In the case of China, the developments of the DR sector arose due to the difficulty of installing generation capacities with a fast enough pace to keep up with the high annual energy consumption growth [43]. Through the encouragement of energy storage in the form of hot water or ice in Beijing from 1997 to 2003, the on/off peak demand ratio was improved and 67% of the energy for heating was consumed during off peak periods. China, however, has a rather underdeveloped DR sector as a result of poor regulatory framework and a lack of stable funding mechanisms [14]. On a similar note, from 2007 onwards, New Zealand’s transmission system operator (TSO) Transpower has been involved in demand response, aggregating around 60 MW by 2010 and later increasing the capacity to 200 MW in 2013 [44]. There is no clear indication of the extent to which this capacity is based on P2H, nevertheless.

In 2009, the Pacific Power and Gas project tested the use of air conditioners in nearly 2,000 residential households to provide ancillary services [45]. Although the project demonstrates the capability of P2H DR to provide real-time balancing, the time scale of the reported response in [45] falls below the short-term requirements for frequency stability of the power system. In a power system with conventional generators, frequency response upon a disturbance is an automatic and nearly immediate action from the generation side. In 1980, Schweppe et al. patented the Frequency Adaptive Power Energy Rescheduler (FAPER) device, which enabled a similar response from demand side appliances [46]. In line with this idea of controlling the demand side for frequency response is the Pacific Northwest GridWise™ Testbed Demonstration Project [47].

Table 2. Review of P2H DR projects during 1990s – 2010

Project	Year	Location	Size	Technology	Communication	Objective	Implementation	Takeaway
Sacramento Municipal Utility District Residential Peak Corps [40]	1992	US	19,130 participants	Central air conditioning loads	Radio ripple control, VHF radio	Peak clipping	On/off cycling	- 100 MW peak reduction (2145 MW peak) - 30/60 min or 40/60 min cycling pattern - 12-20% monthly savings
United Power Association Off-Peak Program [40]	1992	US	5,107 space heaters, 21,077 EWH, 12,764 dual fuel heaters, 15,979 ACs, 317 irrigation pumps	space heaters, EWH, dual fuel heaters, ACs, irrigation pumps	Radio ripple control, VHF radio	Peak clipping	On/off cycling	- 92 MW peak saving (647 MW peak) - 15/25 min cycling pattern - Charges reduced to 3.4 c/kWh from 4.5 c/kWh
Buckeye Power Residential Load Control [40]	1992	US	$10 million	EWH, space heaters	Radio ripple control, VHF radio	Peak clipping	On/off cycling	- 81 MW, 14 MW peak reduction (956 MW peak) - 12/30 min cycling pattern - No incentive

Table 2. Review of P2H DR projects during 1990s – 2010 (contd.)

Project	Year	Location	Size	Technology	Communication	Objective	Implementation	Takeaway
Houston Lighting & Power [42]	1993	US	20,000 new installations in 1993	AC, heat pumps	Radio ripple control, VHF radio	Peak clipping	On/off cycling	- 185 participants in pilot program -Expected 1.46 kW load reduction per participant - Free service and cash payment to incentivize participants
Beijing [14]	1997-2003	China	(1) 77,431 consumers (61.69%) (2) N.A. (3) 23,175 residential consumers (4) 600 locations, 2800 MW connected	N.A.	(4) Internet	- Load shifting	(1) TOU tariffs (2) Load interruption (3) Support of energy storage (hot water and ice storage) (4) Direct load control	(1) 700 MW shifted (2) 100 MW shifted (3) improvement of on/off peak demand (67% of heating demand was off peak) (4) 500 MW
Danish pilot study [48]	2004	Denmark	25 households	Electric heating	N.A.	Peak clipping	Load curtailments	- 5 kW per consumer demand reduction possible

Table 2. Review of P2H DR projects during 1990s – 2010 (contd.)

Project	Year	Location	Size	Technology	Communication	Objective	Implementation	Takeaway
Pacific Power and Gas [45]	2009	US	2,000 households	AC	Communicating thermostats and programmable load control switches	- Load curtailment - Ancillary services - Real-time balancing	- On/off control - Power modulation	- Financial incentives offered on a $/kW basis - Provides different DR offers
Pacific Northwest GridWise™ Testbed Demonstration Projects, part ii [47]	2007	US	200 devices	50 EHW, 150 washing machines	Autonomous, grid-responsive controller Grid Friendly™ appliance controller	Frequency response	Power modulation	- 0.25 sec response time in case of a sudden drop of frequency - Responded to deviations greater than 0.003 Hz

2.4 Since 2010

For the period from 2010 – 2016, Kohlhepp et al. [9] have surveyed 16 field projects focusing on P2H and thermal storage. They distinguish three groups of projects: (i) projects focused on real-time electricity markets, real-time trade and transactive control, (ii) projects focused on self-sufficient communities, virtual power plants and microgrids and (iii) projects interested in the potential of using thermal energy storage to provide benefits to distribution grids. The brief summary of first two groups, their DR control mechanism and the type of DR control (indirect or direct), based on the results in [9], have been included in Table 3.

Within the projects focused of real-time balancing and load smoothing (group 1), an emerging interest in transactive control is evident. Transactive control, a concept from the transactive energy field of research, focuses on managing the resources on the demand side (both generation and consumption) in a transactive market [49]. The envisaged concept of transcative energy should enable a system which is decentralized, autonomous and automated [50]. Only three of the projects within this group had some form of direct load control (Couperus, OlyPen and EcoGrid EU). All of the project from Table 3, however, depended on some form of indirect DR, either as real-time pricing (RTP), critical peak pricing (CPP), real-time trade (RTT) or TOU. The second group of projects, on the other hand, focused on deploying the P2H resources in order to become more self-sufficient and utilize the benefits of aggregation. For instance, the project Your Energy Moment [51], focused on load shifting and improving local self-consumption through PVs and heat pumps. The results obtained from 50 households showed that, by using energy management systems, the peak load can be reduced up to 48%. The EcoGrid EU project [52], on a similar note, found demand flexibility of up to 27% per hour. The project Linear [51,53] has an important finding relevant to the issue of consumer behavior. Namely, its results suggest that manual DR can be too invasive and result in consumer fatigue.

Table 3. Summary of P2H projects from [9] and the type of DR action (2010-2016)

Project	DR control	Indirect DR	Direct DR	Ref.
Couperus[1]	DLC, RTT	✓	✓	[51,54]
AEP Ohio gridSmart[1]	RTT	✓		[55]
Pacific Northwest (PNW SGDP)[1]	RTT	✓		[56–61]
Olympic Peninsula (OlyPen)[1]	DLC, TOU, CPP, RTT	✓	✓	[62]
Powermatching City[1,2]	RTT	✓		[51,63,64]
EcoGrid EU[1,2]	DLC, RTT	✓	✓	[52]
Your Energy Moment[2]	TOU	✓		[51]
Linear[2]	TOU, DLC	✓	✓	[51,53]
Smart Gotland Grid[2]	DLC, TOU	✓	✓	[65]
Nice Grid[2]	Alert	✓		[66]
E-Energy[2]	TOU, CPP, RTP	✓		[51,67]

[1] = real-time electricity markets, real-time trade and transactive control, [2] = self-sufficient communities, virtual power plants and microgrids

Most of the projects mentioned above, with the exception of Nice Grid in France (2,500 households) and Pacific Northwest Smart Grid in the US (60,000 households), count a few hundred households at most. Among the larger projects are also the Municipal plants for DR (1 GW load) and Tiko in Switzerland (4,500 households in 2017 [9], more than 7,000 in 2020 [68]) and Modellstadt in Germany (8,150 end users). The Tiko platform is rather interesting in the sense that it has passed a test stage and is currently on the market, operating as a virtual power plant that provides load reduction and frequency response. The platform can combine different end-use appliances, among which are those that couple the power and the heat sector, such as electric water heater, heat pumps etc. In that sense, Tiko is comparable with the US Pacific Northwest GridWise™ Testbed Demonstration Projects [47] in terms of concept, but larger in terms of size and actual implementation.

The advancement of communication infrastructure and its use is evident in these projects when compared to earlier field projects, as shown in Table 4. The Pecan Street project, for instance, is an ongoing project initiated in 2009. Smart thermostats and home energy management systems (HEMS) are used within the project, which communicate with a smart meter. The HEMS can be implemented using the ZigBee standard. Smart thermostats are used in CSP Energy Smart Thermostat programme (Honeywell thermostats) [69] and Austin Energy "Rush Hour Rewards" programme (Nest thermostats) [81]. Other HVAC deferrable devices are used in the Austin Energy "Load Cooperative Program" [21,82] in which consumers are reimbursed 1.25$/kWh for the load curtailed with a notice given 60 minutes in advance. In Australia, air conditioners are used for peak demand reduction in the Energex PeakSmart project [70], and the *Cool*Saver project of Ausgrid [71] and Endeavour Energy [70]. These projects demonstrate peak demand reductions up to 30%, with around 1 kVA demand reduction potential per participant. The *Cool*Saver project included 109 participants in 2013, (the number decreased to 79 in 2016 due to residents moving out), while no data could be found on the scale of the other project. Consumer participation was incentivized via direct payments, up to $500 cash, in the case of Energex PeakSmart, and $60 bonus and limited free AC service, in the case of *Cool*Saver.

Table 4. Review of additional P2H DR projects since 2010

Project	Year	Location	Size	Technology	Communication	Objective	Implementation	Takeaway
Pecan Street [72]	2010	Texas, US	over 1000	PV, micro-CHP, HP, smart appliances, battery storage, EV	-HEMS, smart meters, smart thermostats	- Increase self-consumption - Load shifting	N.A.	- Consumers can easily loose interest in their consumption data
Energex PeakSmart [70]	2013-	Australia	N.A.	AC	Ripple control, smart meter, ZigBee wireless interface, AS4755 standard	Peak clipping	Cycling	- 13%-20% remand reduction - 0.9 kVA per customer - Up to $500 cash customer incentive
Endeavour Energy [70] and Ausgrid *Cool*Saver [71]	2011-2016	Australia	109 in 2013, 107 in 2014, 90 in 2015, 79 in 2016	AC	Ripple control, smart meter, ZigBee wireless interface, AS4755 standard	Peak clipping	AC operated at reduced mode (50%) during peak demand	- 1.5 kVA for ACs >10 kW - 0.7 kVA for AC between 4-10 kW
Tiko platform [9,68,73]	2014-	Switzerland	More than 7,000 in 2020	HP, EWH etc.	K-Box, M-Box, tiko platform, PLC at consumer premises, 3G or Internet between consumer and platform	Peak clipping, primary and secondary frequency control	On/off control	- Difficulty in weather forecast may lead to conservative capacity bids - P2H resource combined with hydropower

Table 4. Review of additional P2H DR projects since 2010 (contd.)

Project	Year	Location	Size	Technology	Communication	Objective	Implementation	Takeaway
CSP Energy Smart Thermostat programme [69]	ongoing	Texas, US	N.A.	HVAC	Honeywell smart thermostat, Wifi	Peak clipping	On/off cycling	- Equipment free of charge - Does not provide incentives; ensures reduction of heating/cooling costs above 10%
Austin Energy "Rush Hour Rewards" [15,74]	ongoing	Texas, US	2,000 in 2013	Central AC	Nest Smart thermostat	Peak clipping	Temperature control	-Consumer gets paid $85 to participate - Specific hours in summer, holidays and weekends - Guarantee of control events are not longer than 2h
Austin Energy "Load Cooperative Program" [15,75]	ongoing	Texas, US	N.A.	HVAC and other deferrable devices	LAN, WAN, OpenADR 2.0b, smart meter	Peak clipping	Temperature control, on/off cycling	-1.25$/kWh for load curtailment with 1h in advance notice

4. DISCUSSION

The reviewed projects were derived from peer-reviewed literature and utility reports that were available online. Although extensive, the review is by no means complete. The reason behind this is that not all of P2H DR programmes implemented worldwide by companies have been reported in peer-reviewed literature or in a traceable online form. As a result, to account for all possible projects using the methods discussed in this paper would be difficult, mainly due to the lack of data, but also due to the format restrictions of this paper. Despite the limited sample of the 34 projects analyzed here, the review is chronologically and geographically diverse. The reviewed projects are dominantly focused on experiences from the US and the EU, but also draw from experiences in Australia, New Zealand and China. Because the projects are balanced in terms of technology, objective and local conditions, the reviewed sample of projects can be considered a good representation of the real life applications of P2H DR programmes.

4.1 Technical capabilities of P2H DR

One of the main challenges faced by market participants with low experience in planning DR actions is the use of extensive assumptions [76]. This subsection aims to shed light on the technical capabilities of P2H DR based on the reviewed empirical experiences. Literature shows numerous benefits of utilizing P2H as a flexibility resource for reducing peak demands in the power grid [77] and imbalance costs in virtual power plants [78], but also in providing load balancing [79], frequency regulation [80] and improving local self-consumption [81].

In the P2H DR projects reviewed in this paper, the objectives most commonly pursued can be classified as :

- load reduction (peak clipping),
- load shifting and self-consumption,
- real-time balancing and frequency response.

4.1.1 Load reduction

The success of direct load control of P2H devices for load reduction depends on the technical potential of each consumer (per consumer load reduction), but also on the scale of DR deployment (total load reduction).

4.1.1.1 Technical potential for load reduction per consumer

Table 5 shows the load reduction and controllable power, per consumer, of the reviewed field projects. The data has been drawn from the practical experiences with direct load control of the P2H programmes. The projects in Table 5 are selected on the basis of data availability and are ordered chronologically.

The average controllable power per consumer depends on the controlled P2H technology, its capacity, local weather conditions and the type of control applied (cycling control, shedding etc.). The Houston Lighting & Power DR programme, for instance, estimated a value of 1.46 kW load reduction per consumer [42]. The Power and Light programme shows that AC shedding provides greater average per consumer reductions (2.2 kW) than cycling the ACs on/off (0.9 kW) [39]. The projects Energex PeakSmart [70] and *Cool*Saver [70,71] in Australia demonstrate similar results. They show that AC cycling enables load reduction per consumer of about 0.7 – 0.9 kVA (for smaller AC units) and 1.5 kVA for AC units with capacity above 10 kW. In wintertime, a Danish field project [48] estimates that households with electric heating can enable load reduction up to 5 kW. This would mean that for a typical winter day in Denmark, the peak load could be reduced by 250 MW, given that 50% of the Danish households that use electric heating participate [13]. Other countries with high shares of electric heating, such as Sweden, Finland and Norway, have a strong potential to offer such flexibility as well [82]. Using ground-source heat pumps, the Couperus project, demonstrated a controllable capacity of up to 21% of the nameplate power.

Table 5. Load reduction per consumer in field projects

Case	Controllable capacity per consumer
Houston Lighting & Power [42]	1.46 kW
Florida Power and Light [39]	0.9 kW (AC cycling) 2.2 kW (AC shedding) 0.5-0.8 kW (EWH shedding)
Danish pilot study [48]	5 kW
Energex PeakSmart [70]	0.9 kVA
Ausgrid *Cool*Saver [70,71]	- 1.5 kVA (>10 kW ACs) - 0.7 kVA (4-10 kW ACs)
Pacific Power and Gas [45]	0.65 kW
Couperus [51,54]	up to 21% of nameplate power

4.1.1.2 Demonstrated peak load reduction

The scale of the peak load reduction depends on the number of participants in the DR action. Historically, marketing has helped increase the number of participants [42], but consumer acceptance and trust in the utilities, along with the demographics of the population are strongly influencing factors [39]. Table 6 shows the total load reductions that have occurred in different field projects and utility programmes, represented as a percent of the total peak demand when no DR action was in place. The variance of the load reductions presented in Table 6 also depends on the representation of the results.

The load reduction of the utility programmes (Florida Power Corporation, EDF France, Sacramento Municipal Utility District Residential Peak Corps, United Power Association Off-Peak Program and Buckeye Power Residential Load Control) is represented in terms of the total peak load, both of participating and non-participating consumers. On the other hand, the load reduction of field projects (Energex PeakSmart, Endeavour Energy *Cool*Saver, Your Energy Moment (YEM), Shanghai project and Kitakyushu Smart Community Creation Project) is represented in terms of the load of the consumers which are part of the project.

In absolute terms, the utility DR programmes often have a greater scale than research pilot projects. DR programmes range from tens of thousands [38,40] to millions of participants (in the case of France [41]), resulting in significant load reductions. The scale of the field projects, on the other hand, is usually in the order of tens to hundreds of participants, as their main goal was to enhance the knowledge and improve the experience with P2H DR.

Table 6. Total peak load reduction in field projects

Case	Peal load reduction
Florida Power Corporation [40],[38]	10.33%
EDF France [41]	1.5%
Sacramento Municipal Utility District Residential Peak Corps [40]	4.66%
United Power Association Off-Peak Program [40]	14.22%
Buckeye Power Residential Load Control [40]	1.46%
Energex PeakSmart [70]	13%-20%
Endeavour Energy *Cool*Saver [70]	30%
Your Energy Moment (YEM) [51]	<48%
Shanghai project [9]	10-15%
Kitakyushu Smart Community Creation Project [9]	20%

4.1.2 Load shifting and self-consumption

Load shifting can be strategically implemented via price signals to reshape the load curve, or it can be implemented locally, by one or more consumers, to improve energy autonomy and self-consumption. TOU tariffs, for example, have been used to achieve more long-term and predictable load shifting in the UK [13] and France [41]. As a complement to the base load generation system, they have been combined with time switches which were used to schedule the operation of end-use appliances such as electric water heaters. Many new appliances sold today, such as heat pumps, have integrated time scheduling controls and do not require additional switches as legacy equipment did. These built-in advance controls can also be combined with TOU tariffs and have also been tested in more recent projects (YEM, Linear, Smart Gotland Grid, E-Energy).

The project YEM investigated the potential for load shifting and self-consumption of household with heat pumps, smart washing machines and 1.5 kW PVs and found -18%/+31% user load flexibility [9]. Consumer power flexibility of -27% per hour has also been reported in [9] from the EcoGrid EU project [52]. A comprehensive review of other works on improving self-consumption in buildings with PVs has been provided in [81].

Load shifting can also be achieved through other structural demand side measures, such as encouraging energy efficiency or storage. In Beijing, China [14], the encouragement of energy storage in the form of hot water of cold storage contributed in the improvement of on/off peak demand ratio (67% of heating demand was off peak). The demand side measure involved 23,174 residential consumers. At the same time, 77,431 consumers participating in TOU tariffs in China enables a shift of 700 MW load.

Distributed small capacities have a limited ability to shift energy demand over large periods or among seasons. Seasonal shifting can more easily be achieved through larger capacities, such as municipal and sewage plants, which can sell their flexibility on the reserve market [9]. With the digitalization and decentralization of the energy sector, RTP and RTT have emerged as tools which may contribute to real-time balancing and facilitate self-consumption. RTT and RTP has been tested in Powermatching City, EcoGrid EU and E-Energy, Couperus, AEP Ohio gridSmart, PNW SGDP and OlyPen, as found in [9].

4.1.3 Real-time balancing and frequency response

Indirect, price-based DR can be insufficient for real-time balancing, when action is required within small time-steps [9]. Direct load control and decentralized mechanisms can be more useful when a large number of P2H units are aggregated on the demand side. This can improve both real-time balancing as well as the inertia of the system. A review of these possibilities and challenges has been provided in [83]. Electric water heaters, air conditioners, heat pumps and refrigerators are most suitable to be controlled in a decentralized manner, similarly to the concept of the FAPER device [46]. Simulations of this principle have explored the viability of using TCLs in California, US [84] or the UK (heat pumps [85] and refrigerators [80]) using distributed control.

There are a number of pilot projects and companies on that market whose value proposition is based on TLC control using two-way communication. The pilot project of Pacific Power and Gas [45], showed that consumption data can be transmitted in near real-time, giving market actors information about the availability of the DR capacity. The project included 2,000 households and tested the potential of domestic air conditioners to provide ancillary services. The results showed that air conditioner load control can be started within 1 minute and ramp up to maximum capacity in 7 minutes, while the measurements of the aggregated demand can be transmitted to operators in nearly real-time.

However, because the available capacity of P2H DR resources is weather dependent, a precise forecast of the weather is required when the DR capacity needs to be planned ahead. Tiko [73] is a Swiss aggregator platform dealing with peak shaving and primary and secondary frequency control [68]. Its operational experience shows that estimating available capacity is difficult to achieve when capacity bids are required in advance of longer time horizons (e.g. two weeks). To overcome this issue, capacity planning can be done conservatively and, as in the case of the Tiko business model, the controlled TCLs can be combined with hydropower generators.

Finally, the Pacific Northwest GridWise™ Testbed Demonstration Projects showed that decentralized control of electric water heaters and washing machines can be used to provide frequency response [47]. The underlying idea is that, unlike bulk reduction of large loads, the distributed control of TCLs can be performed more smoothly. The results showed 0.02 kW – 0.2 kW controllability per washing machine and 0.1 kW – 0.7kW per water heater, with little to no inconvenience for the user. The project reports 0.25 sec response time in case of a sudden drop of frequency.

4.2 Enabling ICT infrastructure

In Michigan’s load control programme, when a communication infrastructure was not in place, technicians were sent on-site to manually set and schedule the operation of consumers’ devices [35]. This was an early, rudimentary and time-inefficient implementation of P2H DR, considering that the DR resource is distributed at each consumer’s premises. However, the control of the demand side is much more easily achieved when a suitable ICT infrastructure is in place. Based on the reviewed projects, this section briefly discussed the developments of the ICT infrastructure as a key enabler of P2H DR.

According to [22], the communication technologies for DR, in general, are clock-based controls, communication over power lines (PLC ripple control), radio communications (radio ripple control), telecommunications systems, voltage reduction and frequency reduction.

With the exception of voltage reduction, all of these technologies were encountered in the reviewed projects, as shown in Table 7. Table 7 also takes into account the development of the cited projects throughout time by integrating references to the period in which they have taken place in. The communication technologies can be deployed within the home area network (HAN), neighborhood area network (NAN) or wide area network (WAN) [15]. The findings show that the issues of the ICT infrastructure [45] that have been reported in the past have been related to cost [86], reliability [39], scale [87] and diffusion [80].

Table 7. Communication technologies used and their evolutions throughout time

Case	Load reduction
Clock-based controls	[13][b], [41][b], [45][c]
PLC ripple control	[22][a], [39][b], [41][b], [65][d], [68][d], [70][d], [71][d]
Radio ripple control	[13][b], [35][b], [40][b,c], [42][c], [60][c], [63][d]
Internet and telecommunication systems	[16][d], [14][c], [65][d], [68][d], [69][d], [70][d], [71][d], [72][d], [74][d], [75][d]
Frequency reduction	[46][b], [47][c]

[a] = until 1950s, [b] = during 1960s-1980s, [c] = during 1990s-2010, [d] = since 2010

The early P2H DR programmes reported varying success in communicaton reliability (97% reliability in [38,40], and major failures of receiver devices in [35]). The reliability of ICT has been significantly improved since these early attempts, considering the stringent requirements imposed on the equipment [88]. With regards to cost, the consumers of the early programmes were equipped with timer switches or radio control devices [37] costing around $50 to $150 at the time of writing of [34]. The communication and metering infrastructure is still considered the major investment for DR at end users [86]. Many of the existing projects were implemented using ripple control and clock-based systems, as shown in Table 7. In more recent projects, a shift towards Internet and telecommunication systems is noted. This shift is accompanied by the deployment of smart metering infrastructure. While some projects, such as [70] and [71], combine ripple control with smart meters or the Internet, outdated ripple control infrastructures, such as that in the Czech Republic [89], have been found to possible hinder the deployment of more advanced demand response actions.

Smart meters, smart plugs and smart appliances with two-way communication, as well as smartphone apps have been tested and widely deployed in the projects implemented since 2010, as shown by CSP Energy Smart Thermostat [15,69] and Austin Energy "Rush Hour Rewards" [15,74]. Smart meters play a crucial role, as a gateway between the HAN and the outside networks. The PeakSmart [70] and the *Cool*Saver projects [71] are both using the ZigBee protocol within the HAN, while the smart meter is the gateway which enables two-way communications with the outside. However, laying down the necessary communication infrastructure poses significant challenges in terms of scale. In the case of the "tiko" device, vendors and utility companies are used as intermediaries to scale-up the diffusion of proprietary hardware. The value proposition to the end-consumers is offering the ability to monitor the electricity consumption in real-time. On a strategic level, the EU planned to roll out at least 80% smart electricity meters by 2020 as part of the advanced monitoring infrastructure (AMI) [90], but the process has been rather slow and faced more hurdles than expected [91].

There are different protocols and standards for all scales of communication [15], such as the OpenADR (used in Austin Energy "Load Cooperative Program" [82]), approved by U.S. Department of Energy (DoE) or the AS4755 standard, used in the Australian PeakSmart [70], and *Cool*Saver projects [71]. However, the data traffic can be a challenging task for the existing infrastructure, especially when two-way communication is considered, as it can increase the necessary investment costs for communication infrastructure. To avoid such hurdles, an approach based on data aggregation and reporting only the changes in consumption could significantly lower data traffic [87].

Darby [92] notes that a viable DR application requires not only good communication between devices, but constructive inter-personal relations and interactions as well. Most of the challenges related to the maturity of separate technologies have largely been overcome, as developments has gone beyond the unreliable radio receivers discussed in [35]. On this point Paterakis et al. [15] claim that "*the key technologies for the implementation of DR have already been developed*". The pressing matters at this stage are related more to need of further standardization and interoperability [93].

4.3 Change of framework conditions

The framework conditions in the power sector have roughly evolved in three general periods (i) a period of a regulated power sector, (ii) a period when the power sector underwent deregulation and (iii) a period when the power sector is liberalized. The progression of countries from one period to another, and within each period largely differs.

Within the first period, for instance, vertically integrated utilities used P2H DR for reducing peak demand (i) at time of high incremental generation cost and (ii) to alleviate generation shortages [39]. In these circumstances, the success of DR programmes, especially in the US, was arguably the result of the simple implementation (based on minimal consumer input) and the fact that P2H was more cost-effective compared to expensive peak plants in the fossil based system. Hence, the wide deployment of P2H as a DR resource comes, among other reasons, from the lack of competing flexible resources on the demand side. For instance, batteries were not as widely deployed at the time. When other flexibility resources, such as pumped hydro energy storage, were available besides P2H, a declining use of DR was noted. The declining use of DR in these cases was based on a top-down decision which is typical of vertically integrated companies [35]. The experiences from this period are most prevalent in the US, while Europe focused more on TOU tariffs and other indirect actions, thus offering limited documented evaluation [13].

By the 1990s the power sector began to restructure. In the US, the period around the restructuring of the power sector changed the perceptance of P2H DR, and DR in general, due to the uncertainty it introduced and the burden it posed on companies to prove economic capability. In 1996, Nadel et al. [37] argued that incentive-based DR programs would often be scaled back or eliminated. Despite these concerns, results from 1989-1993 show that the restructuring of the power sector in the US did not reduce DSM expenditures of utilities (about 1.5% of revenues). However, in the case of the US, the form of DSM expenditures changed, and not all financing was dedicated to the residential sector, as discussed in [94]. During this time, focus was found to shift from the residential to the industrial sector for demand reduction, while the commercial sector became more interesting than both the residential and industrial sector in terms of energy savings. Although this trend is not specifically related to P2H, considering that P2H was responsible a significant portion of DR programmes at the time, it explains the decreasing interest in residential P2H DR actions in the US [94]. As utilities adapted to the deregulated environment, they had to demonstrate economic capability, thus making additional longer-term investments not a priority of the time.

In the EU, around this time, the French-German debate on the electricity market liberalization came to a conclusion and led to the opening of markets in December 1996 [95]. Actors in the energy sector approached the market liberalization at different speeds in each Member State and faced significant uncertainty due to new risks in this environment [96]. Combined with the lack of past experience, little deployment of direct DR actions from P2H in Europe can be found in the period around the market liberalization, as discussed in [97] and as found by our review. China differs from the US and the EU as it is simultaneously faced with developing the generation and transmission infrastructure and restructuring the market. In this aspect, in 2003 and 2004 mandatory load reduction were performed based on government orders [14] but there is a tendency to move towards a more market-based approach [43].

Regarding the deregulation period, Nadel et al. [37] noted that "*the role of DSM in serving small consumers will depend in particular on how local distribution companies are restructured*". Although this point was made with US companies in mind, its validity is transferrable for EU Member States. After the power sector liberalization in the Czech Republic [89], for instance, the ripple control infrastructure is operated by the DSO. This does not enable the true DR potential of the P2H resources to be captured since the end-consumers cannot access suitable markets.

The introduction of electricity markets and new actors (e.g. aggregators) presents added complexity to the operation of the energy sector, but also new opportunities for P2H DR. With the increased penetration of renewable energy and newly acknowledged price volatility [98], P2H DR can be used to compensate for the reduced inertia of the power sector [47] and contribute to real-time balancing [9]. Most of all, the market can make use of its proven capability for load reduction, demonstrated both by early DR programmes (Subsections 2.1 and 2.2), but also by more recent ones (e.g. China [43], Australia [70,71], Switzerland [73]). However, there are differences in the pace with which regions approach the developments of DR enabling markets, for instance in the EU [89] and in the US [99]. This makes the policy landscape messy and difficult for knowledge transfer and development of plug-and-play solutions.

The market barriers comprehensively discussed in [15] that may be most relevant to the EU and the US, include the minimum resource bid size, possibility of aggregation, bid direction (symmetrical bids), number of calls, load recovery period, response time, duration of response, fixed trading charges, membership and entrance fees. Suitable market design [99] has been shown to be as crucial as the actual implementation of the rules and regulations [89]. To successfully provide ancillary services with air conditions, for examples, [45] notes that a decrease in the operating intervals and a re-defining of the agreements with consumers are required. Both of these points are deemed to be framework-related barriers, which "*can be easily overcome*" [45].

4.4 Critical remarks

The manner in which heat pumps, electric water heaters, air conditioners and other TCLs are used by end-consumers allows one to alter their electricity demand for short periods, without significantly affecting the comfort of the end-consumer. When this is done by an actor other than the end-consumer, the service and the inconvenience caused by this action should be compensated in a monetary or nonmonetary manner. Altering the energy use over a large population of devices can significantly improve the flexibility of the energy system when performed in a coordinated manner, as shown by the findings of Subsections 4.1, 4.2 and 4.3. As a result, the potential of P2H devices for serving as a DR resource has been recognized since the 1950s.

In the early DR programmes, P2H devices were among the most prevalent deferrable and flexible resources on the demand side (especially in the residential sector) which could provide significant scale. As they couple the power and the heat sectors together, their use has recently drawn attention in the field of energy sector coupling. However, the sector coupling provided by P2H DR is a means to an end, the end being greater flexibility of the energy system. Hence, the sector coupling is a consequence of the large diffusion of P2H devices at end-consumers. With that in mind, the synergies between different energy sectors have *de facto* been exploited for more than 40 years, much earlier than the emergence of the concepts of smart energy systems and energy sector coupling. We see, nevertheless, the formal introduction of this field of research as academia's response to the acknowledgement of its benefits. It shows that researchers have been picking up on the areas of natural inter-sectoral cohesion and have explored more advanced forms of their utilization.

The empirical evidence shows that P2H DR has been deployed in large-scale programmes and pilot projects to achieve load reduction, real-time balancing and ancillary services, such and frequency response. Load reduction has been the simplest and, given the fact that it has been used in commercial utility programmes, the most widely implemented functionality. Load reduction and peak clipping are still major drivers for P2H DR deployment and dealing with capacity limitations in China [43], Australia [70,71] and Switzerland [73]. The result shows that direct load control can be more effective on smaller time scales, making it useful for dealing with capacity limitations and balancing the variability of RES in near real-time. This has stimulated a resurgence of direct load control programmes. The projects in Australia, for instance, are similar to the early US programmes, but are based on more sophisticated control and communication technologies. At the same time, price-based DR has been found suitable for reshaping the load curve indirectly. While electric storage heaters were once incentivized for this purpose, thermal inertia of buildings and dedicated thermal storage units can be used in the future. Because price-based DR depends on human interaction, it can be more challenging and unreliable on smaller time scale.

This fact has been clearly acknowledged by Kohlhepp et al. from their review of large-scale P2H field projects from the period of 2010-2016. They additionally note that P2H should be able to provide frequency response via decentralized control, but that they are unaware of pilot projects of this nature [9]. Based on our review of similar projects over a longer time horizon, we fill this gap by discussing the existing enabling technologies, such as the FAPER, developed as early as the 1980s, and the pilot of Pacific Northwest GridWise™ Testbed which is based on a similar approach [47]. The authors of [47] make it clear that "*technical feasibility is not standing in the way of applying distributed, frequency responsive appliance load controllers*". This does not, however, imply that distributed control of P2H is a silver bullet solution or that all attempts of using this technology will succeed. There are challenges posed by the market [89], the need for aggregating a large number of devices and the competition from other demand side flexibility resources, such as batteries [100]. An example is the UK firm ResponsiveLoad Ltd., with the patent [101] mentioned in [102] which was incorporated in 2012, but later dissolved in 2015 [103].

For meeting the challenges of high RES energy systems, P2H DR can be used as a demand side resource equivalent to that of the generation side. Sullivan et al. mention that the obstacles for large-scale deployment of this approach can be overcome and that "*it will be necessary to re-market the load control programs*" [45]. In a market environment, operating DR as a controllable resource for ancillary services requires making capacity bids in advance. The experiences of the Swiss Tiko demonstrate that these market bids are a challenging task when it comes to P2H DR, as they are inevitably based on a weather-dependent resource and the weather is not easily forecasted for longer durations in advance. However, Tiko uses both hydrogeneration and P2H DR to complement each other in providing more reliable capacity [73]. This is different from the top down approach of Detroit Edison to downgrade demand side resources because it had hydro generators available in the 1970s and 1980s [35].

It seems that the issue of consumer acceptance has persisted over time [104] and has been recognized as the "*greatest challenge*" for DR deployment in [15]. The findings of [105] and [106] on this issue are similar. Consumers' distrust in certain utilities can be a significant barrier for their participation in DR actions [107]. However, lessons can be learned from successful programmes in order to overcome this barrier, such as the programmes reviewed in this paper. Our review shows that, when the framework conditions are suitable, the added value of P2H DR can be shared with the consumers and significant consumer acceptance can be achieved.

The systematic review of 34 project shows that necessity for adequate infrastructure capacity drives the deployment of P2H DR at scale. Most commonly, this necessity came from a lack of generation or distribution capacity, as shown by the US experiences, or from the need to reshape the demand curve so that it suits the generation system, as shown by the experiences in early UK and France. The deployment has been realized through top-down approaches, such as voluntary programmes of vertically integrated utilities (e.g. in 1960s-1990s), government decisions (e.g. in China) or through a competitive market (e.g. through aggregators). The future energy system will have greater needs for real-time balancing of the variable renewable energy sources. These challenges have been addressed by recent and ongoing projects, but additional projects are required to further explore them. Both the utility programmes and the research projects show that the control and information technologies are mature enough to enable the deployment of P2H DR. Possible issues with ICT may arise not from the lack of technology, but from a lack of local know-how or a lack of equipment interoperability. Finally, P2H DR deployment may not be suitable where the energy system has other flexibility resources in place. With a somewhat differing view from [9], these findings permit making the claim that the diffusion of P2H DR, where necessary, has been slowed down not by technology, but by the fact that the challenges related to the integration of variable renewable generation are not yet significant enough to put pressure on market actors and regulators to move the economic and policy frameworks forward.

4.5 Outlook and future research

In order to spearhead this development, a deeper understanding of the technical capabilities of P2H DR, as those reviewed in Section 4.1, can contribute to reducing the uncertainty faced by regulators. Field test results have underperformed when compared to simulations [108]. To this end, detailed monitoring and evaluation of P2H devices will be important for developing a better understanding of their weather dependence and availability. Statistical or machine learning algorithms can be applied for developing temperature-dependent consumption profiles to expand the findings of Table 5. Despite the versatility shown by P2H, when market conditions are appropriate, trial and error will likely show that it is more suitable for certain types of niche uses. Distributed P2H DR, as it has been widely used, has demonstrated little potential for the providing long-term flexibility, such as that of seasonal storage. This issue, along with the challenges of aggregating a large number of distributed resources can be, to some extent, overcome by combining them with centralized heat pumps and electric heaters found in larger plants or 4GDH. 4GDH uses lower temperatures and enables various heat sources to be integrated along with seasonal storage. With that in mind, future research should focus on the competitive advantage of P2H with other resources, but also on its complementarity with each of them. On the social side, [92] notes that there is much work ahead in re-approaching the issue of DR on a human level, taking the relations between people and technologies into account.

5. CONCLUSION

This paper reviewed 34 programmes and pilot projects from four continents dealing with DR actions from P2H. Each project was classified with respect to its location, size, technical implementation and objective. The chronological ordering of the reviewed projects enabled key takeaways to be drawn considering the other developments in the energy sector, such as its restructuring. The findings show that DR actions from P2H have demonstrated significant potential both in their use for direct control or as a complement with price-based programmes, such as real-time pricing and TOU tariffs. TOU tariffs have been found suitable for long term reshaping of the demand curve. On the other hand, direct load control has been found more effective than real-time pricing when reaction is required on shorter time scales. Direct load control has a long demonstrated potential in load reduction, ranging from 0.5 kW – 5 kW. Load reduction, both in the regulated and in the market environment, has mostly been used to deal with high incremental generation prices and capacity limitations, but it can also serve in the integration of high shares of renewable energy sources. The review provided additional clarity and filled certain knowledge gaps with regards to using P2H DR for frequency response. Although experiences with frequency response are limited, controllability of electric water heaters, for instance, ranged 0.1 kW – 0.7 kW per device. Communication technologies have been well developed and are a much smaller issue than the lack of an enabling framework.

Given appropriate conditions, P2H has been deployed to achieve large-scale effects, despite the challenges of consumer participation or communication technologies. The findings show that large-scale utility programmes were implemented P2H out of necessity, due to the lack of infrastructure capacity or a lack of flexibility in the system. This is still the case with new programmes for dealing with the demand growth in China or the summer load due to air conditioning in Australia. Moving forward, as the integration of variable renewable energy sources continues, the need for real-time balancing will become even greater at smaller time scales. Many recent research projects have tried to address this challenge, but at a smaller scale than utility programmes. As other technologies develop, P2H DR may not be the dominant flexibility option in the energy system. In order to outline its future role, research should explore its advantages and complementarities compared to other flexibility options. Will P2H develop all of its capabilities equally? Only time will tell.

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