Renewable and Sustainable Energy Reviews 101 (2019) 527–547

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Large-scale grid integration of residential thermal energy storages as demand-side flexibility resource: A review of international field studies

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ARTICLE INFO

Keywords:
Demand response
Load management
Power-to-Heat
Thermal energy storage
Flexibility service
Scheduling
Dispatching
Electricity market
Field testing

ABSTRACT

Power imbalances from fluctuating renewable electricity generators are counteracted by often expensive flexibility services. Heating, cooling, and air-conditioning (HVAC) of buildings, or domestic power-to-heat (P2H), are end uses of electricity that allow flexible load patterns due to the inertia of an attached thermal storage while meeting their quality constraints. Compared to smart appliances or electric vehicle charging, P2H exhibits large and predictable capacities of demand response (DR), because buildings in many countries account for 30–40% of the final energy demand, a large part of which is thermal. Yet, its practical flexibility potential remains largely unknown: is DR from P2H a mature technology for mass usage; is it cost-efficient, socially attractive, and ready to make key contributions to flexibility comparable to backup generators or battery storage? In the present paper, we review recent international field studies that are paving the way from research to practice. These field trials include real customers but have a broader research focus and a wider outreach than rolling out a new DR tariff or program or a specific new technology for DR. Their experience mirrors the technology readiness beyond revenue or policy studies, optimization frameworks or laboratory-scale micro-grids. We analyze the adequacy of the pricing mechanisms deployed for incentivization and remuneration and review the coordination mechanisms for balancing on different timescales including fast ancillary services. We conclude that current control and information technology and economic and regulatory frameworks which have been field-tested do not yet meet the flexibility challenges of smart grids with a very high share ($>50\%$) of intermittent renewable generation.

1. Introduction

1.1. Flexibility services (FS) and Power-to-Heat (P2H)

Decarbonizing the power sector is of particular importance to mitigate anthropogenic climate change. Furthermore, as nuclear power generation is being phased out in Germany by 2022, the bulk of nuclear and fossil base load supply must be replaced by intermittent renewable generation (i-RES, mostly wind and photovoltaics) in the coming decades of the energy transition [1–3]. Power output from i-RES is not controllable and varies due to seasonal and daily weather influences, which are partly predictable. Power imbalances (residual power) remaining due to uncertainties and forecast errors are resolved using flexibility services (FS) [4,5], such as balancing services, contingency reserve, and capacity reserve. The main FS providers [6] are 1) Flexible generators, e.g. thermal backup plants (OCGT/CCGT gas turbines or CHP units), flywheels, pumped hydro, and compressed air energy storage (CAES); 2) Battery storage (dedicated units or demand-driven charging stations, e.g. for electric vehicles), and 3) Flexible demand in the industrial and domestic sectors (residential, commercial, and public buildings). FS are enabled through load management or demand response (DR). Fig. 1 shows a schematic illustration of load management.

Buildings in most industrialized countries account for 30–40% of the final energy demand, a very large part of which is thermal and stems from HVAC [7]. The electricity share varies by technology from 5% to 10% for combustion heating including district heating (mostly due to circulation pumps) to about 100% for electrical storage heating. HVAC electricity often outweighs other electricity demand such as appliances and lighting. The electricity share of HVAC demand is estimated to increase to 20–30% due to the growing installation of heat pumps.

In the present review, all flexible HVAC demand is classified as domestic power-to-heat (P2H). The generation or transfer of heat or

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https://doi.org/10.1016/j.rser.2018.09.045
Received 2 February 2018; Received in revised form 26 September 2018; Accepted 27 September 2018
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Nomenclature

AHU	Air-Handling Unit
AS HP	Air-source Heat Pump
BAS	Building Automation System
BEMS	Building Energy Management System
BRP	Balancing Responsible Party (EU electricity market participant, associated with → TSO)
CAES	Compressed Air Energy Storage
CCGT	Combined-Cycle Gas Turbine (OCGT: Open-cycle)
CHP	Combined Heat and Power
CPP	Critical-Peak Pricing of Electricity
DA	Double-Auction (electricity market)
DHW	Domestic Hot Water
DLC	Direct Load Control
DP	Dynamic Programming (Optimization)
DR	Demand Response
DSM	Demand-Side Management
DSO	Distribution System Operator
DWD	Dantzig-Wolfe Decomposition (optimization method)
ENTSO-e	European Network of Transmission System Operators for Electricity
EPEX	European Power Exchange (wholesale short-term electricity market)
EWH	Electric Water Heater
FERC	Federal Energy Regulatory Commission (USA) for interstate transmission of electricity, gas, and oil
FS	Flexibility Service
GHG	Greenhouse Gas
GPRS	General Packet Radio Service
GS HP	Ground-source Heat Pump
HEMS	Home Energy Management System
HH	Household
HVAC	Heating, Ventilation, and Air Conditioning
i-RES	Intermittent renewable energy source (PV and Wind power)
ICT	Information and Communication Technology
IEA	International Energy Agency
ISGAN	International Smart Grid Action Network (cooperative initiative within → IEA)
LM	Load management
LMP	Locational marginal price
LR	Lagrange relaxation (optimization method)
LV	Low-voltage (distribution grid)
MAS	Multi-Agent System (software architecture)
NSH	Night storage heater (electric room heating)
OpenADR	Open communication standard (USA) for market-based automatic demand response
P2H	Power-to-Heat (electrically operated heat or cold storage used as controllable load)
PCM	Phase Change Material
PCT	Programmable Communicating Thermostat
PEV	Power-Electric Vehicle
PLC	Power-line communication
PM	Power Matcher Software/PowerMatching
PNNL	Pacific Northwest National Laboratory (USA)
PV	Photovoltaics
RT	Real-Time (load dispatch, in contrast to planning/scheduling)
RTP	Real-Time electricity price/pricing
SAIDI	System Average Interruption Duration Index (grid reliability indicator)
SAIFI	System Average Interruption Frequency Index (grid reliability indicator)
SGCC	State Grid Corporation of China (state-owned electric utility monopoly)
SWA	Smart Wet Appliances (washing machines, dryers, or dishwashers with smart start function)
TC	Transactive Control (dispatch of power resources by real-time market)
TCL	Thermostatically controlled load
TES	Thermal energy storage
ToU	Time-of-Use electricity price
TSO	Transmission System Operator
UC	Unit commitment
V2G	Vehicle-to-Grid
VPP	Virtual Power Plant
MINLP	Mixed Integer Non- Linear Programming (optimization with mixed decision variables)

cold in a thermal storage, e.g. a structural building mass, a hot water tank or freezer compartment, is a final use of electricity which must meet quality bounds of thermal safety or comfort within which the thermal inertia allows flexible load patterns. P2H basically can provide positive balancing power by reducing or delaying consumption and negative power by boosting or pushing it forward in time[2] [8]. This is possible on different time scales as shown in[3] [6,9]. DR from domestic P2H can thus help to match electricity generation and residential energy demand.

1.2. Practical flexibility potential

Numerous studies on the theoretical [10–12], the technical [8,13,14], and the economic potential [15,16] of domestic P2H for FS according to a taxonomy by Grein and Pehnt [17] have delivered estimates of energy storage capacity, power deviation, and further parameters that differ widely by geographic and climatic conditions and by their assumptions. To date, the practical flexibility potential of P2H remains unknown: how much will be realizable considering accessibility, cost-efficiency, and social acceptance? Which key drivers help push the practical potential, and which obstacles prevent its full

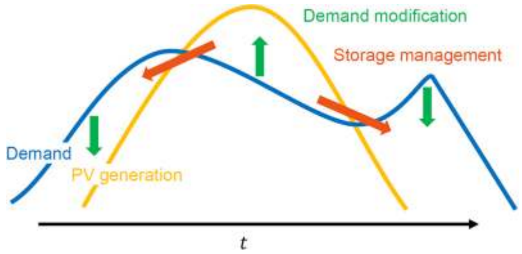

Fig. 1. Illustration of load management (load shifting).

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[2] Our sign convention follows the sign of residual power to be canceled, but is not uniformly adopted. Domestic P2H includes so-called prosumer households that can generate their own power, i.e. through rooftop PV or micro-CHP plant. Together with a hot water storage tank (with optional pure electrical heating), a thermal distribution system, and a thermal mass they form P2H configurations with added capabilities, which offer an extended range of balancing power and more options for local energy management, such as consuming self-generated electricity or selling it on the market.

[3] Time scale reflects the time spans in which some residual load is balanced, which can range from seasonal to diurnal shifts down to the sub-second range (frequency response) and translate into timing parameters of the FS, such as the advance notification by the requester, the response time of the consumer load, the amount of temporal shifting, and the duration of the load profile shifted.

exploitation?

The main research questions of the present review are formulated as follows:

- Is DR from domestic P2H a mature technology for mass deployment and usage, ready to make a key contribution to the required flexibility in future grids when i-RES capacity shares will exceed 50%, that is comparable in quantity and quality to flexible backup generators or battery storage? This question concerns all time scales of FS including frequency response and contingency reserves [18–21].
- Are the basic technologies and regulatory frameworks in place and sufficiently tested as a complete tool chain for mass usage? Regarding technologies, the dispatch of flexible resources must be coordinated with basic load generation to meet the constraints of spatial power distribution and to balance the load based on the most accurate and up-to-date information available. An efficient and secure ICT infrastructure integrates different control levels including the domestic energy management. Regarding economic architecture, markets emerge that through their actors, roles, pricing schemes, and regulations incentivize profitable DR business models but also confine in a purposeful way the future FS business.

Upcoming doubts regarding such an ideal state are partly due to the stepwise rebuild of the FS sector in general. Traditionally, the flexibility needed by grid operators has been defined by programs or products addressing problems that arise in a specific context defined by geography, regulation (EU: ENTSO-E [22], US: FERC), and current generation technology. Examples include [23–26]

- Spinning and non-spinning reserves
- Primary, secondary, and tertiary reserves
- Frequency response
- Regulation and balancing, capacity, resource adequacy, or congestion.

In the future, flexibility needs will arise in more manifold ways, and their effects spread out over different sectors of the electricity system, i.e., generation, storage, consumption, transmission, and distribution [27]. FS are basically public goods but their investors, providers, and beneficiaries remain separated.[4] The total value chain falls apart into heterogeneous markets and regulations. There exist no uniform abstract performance criteria - beyond (signed) balancing power and energy capacity – for tendering FS, specifying orders or comparing offers from diverse providers, such as flexible generators or flexible demand or battery storage. This complicates valuation, competition, and decision-making on equivalence and substitutability.

Several difficulties stem from features that are genuine to the field of domestic P2H. DR programs for HVAC units such as air-conditioners and storage heaters have existed as contracts between utility companies and domestic retail customers since the 1970s. A bewildering variety of DR tariffs is in place worldwide [30], which reflects the past and present w.r.t. generation mixes, market structures, and regulations. In the future, domestic P2H supporting high shares of i-RES might require integrating millions of customers into the smart grid, which become co-responsible for supply security, much more than they used to be. Operational stability and flexibility must then rely either on their goodwill as price-elastic decision makers [31], or on a high degree of DR automation, or on a combination of both approaches.

Regarding the DR market situation, the trend goes towards unbundling different segments, such as generation, transmission, and balancing [28]. Since households, unlike owners of big storage units or flexible generator plants, are too small to trade at a reserve/capacity market individually, they must be pooled by aggregators [32–35]. Barriers to market entrance and serious concerns about soundness of aggregator business based on domestic P2H are persisting [3,6].

In fact, the low capital investment favors domestic HVAC and P2H as FS providers: the thermal demand as a form of electricity end use is already in place and grid-connected, whereas a new battery storage unit or new backup plant represents a dedicated construction. However, the investment required to integrate many HVAC customers into a new ICT infrastructure is significant and will go beyond deploying “smart devices”: firstly, requirements on data privacy, data security and system resiliency[5] and, secondly, advanced automation needs must be met. New standards for home energy management or building automation systems (HEMS/BAS) are required through which the conflicting goals of thermal comfort, energy conservation, and demand flexibility are controlled [41,42]. These HEMS will need to penetrate the residential sector where they are not common today. Not all HEMS development costs but a relevant portion can be attributed to the new functions providing grid flexibility.

The transition process of innovations, investment, and market penetration from traditional HVAC controls to HEMS will largely define the speed of exploiting the available potential. Since FS are public goods benefiting the entire electricity system, nobody may start investing unless expecting rewards [29]. Revenues will be generated from the macroeconomic value of FS which is measured by the total system costs to integrate i-RES at a given penetration level (e.g. 30%, 50%, and 80%). These integration costs comprise grid costs (reinforcement and extension, especially in distribution circuits), real-time balancing costs, and profile costs suffered by other market actors, such as for keeping an under-utilized backup plant as a capacity reserve [3]. Curtailment of i-RES may also incur profile costs.[6] Available estimates of integration costs vary considerably due to the system boundaries and scenario assumptions; e.g. Hirth et al. specify 25–35€/MWh wind integration costs at 30–40% wind penetration [43], and Agora states 5–20€/kW h at 50% wind and PV penetration [44].

Those integration costs that can be avoided through flexibility measures impose a cap on their market value. Domestic P2H will be reduced further by competition with battery storage and flexible backup plants which offer similar services. Since no uniform quality criteria for all kinds of FS currently exist, the market volume of domestic P2H remains unknown. With respect to practical potential, we expect more insight from current transition projects than from policy studies or revenue simulations based on scenario analysis, which require several independent assumptions about a rather distant future.

1.3. Research question and organization of the present review

In this review we approach our research question by evaluating experiences gained in international field studies and demonstration projects of DR flexibility that include a large share of domestic P2H/HVAC. Within the last ten years several large field trials in different countries have been completed, and others are still ongoing. The internal algorithms for resource allocation deployed and under test (the “operating system” dispatching the power resources) and the interfaces to the customers as P2H operators receive particular attention. We expect measured results on DR benefits for distribution grids, analysis of customer interaction (e.g. persistence of involvement, price elasticity of load, impact on life style), and effects that result from the regulatory

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[4] This situation is known as the dilemma of split incentives [28,29].

[5] Cost-effective off-the-shelf Internet components are potentially vulnerable entry points for launching attacks on the grid infrastructure, e.g. [36]. It remains to be seen whether current proposals for smart meters or thermostats or DR control boxes, e.g. [37], meet the requirements imposed on cybersecurity and data privacy. Developing customized solutions for households with higher computational power but restricted functionality [38–40] will be more expensive.

[6] The share of profile costs that can be attributed specifically to i-RES generation is being debated [43].

frameworks and market/pricing structures adopted in the experiments. Regarding experimental design, we are seeking the thin line between shielded laboratory test environments that often exclude real electricity customers and pre-commercial roll-out programs that focus narrowly on a specific technology (e.g. advanced metering) or on a new tariff, but leave little scope for exploring and comparing between different algorithmic (ICT) or regulatory options.

The rest of the paper is organized as follows. Section 2 classifies the thermal storage technologies for residential use and their load flexibility-enabling properties. In Section 3, taxonomies of load management, load scheduling algorithms, and architectures are introduced that will be used to classify the field projects discussed and compared in Section 4. Since load balancing turned out being rooted in a common micro-economic platform for real-time pricing of electricity in several field projects, this approach will be evaluated and discussed in more detail in Section 5. Experiences from field trials in different regions are then summarized and evaluated; conclusions on the maturity of domestic P2H as FS providers are drawn in Section 6.

2. Thermal storage technologies for residential use

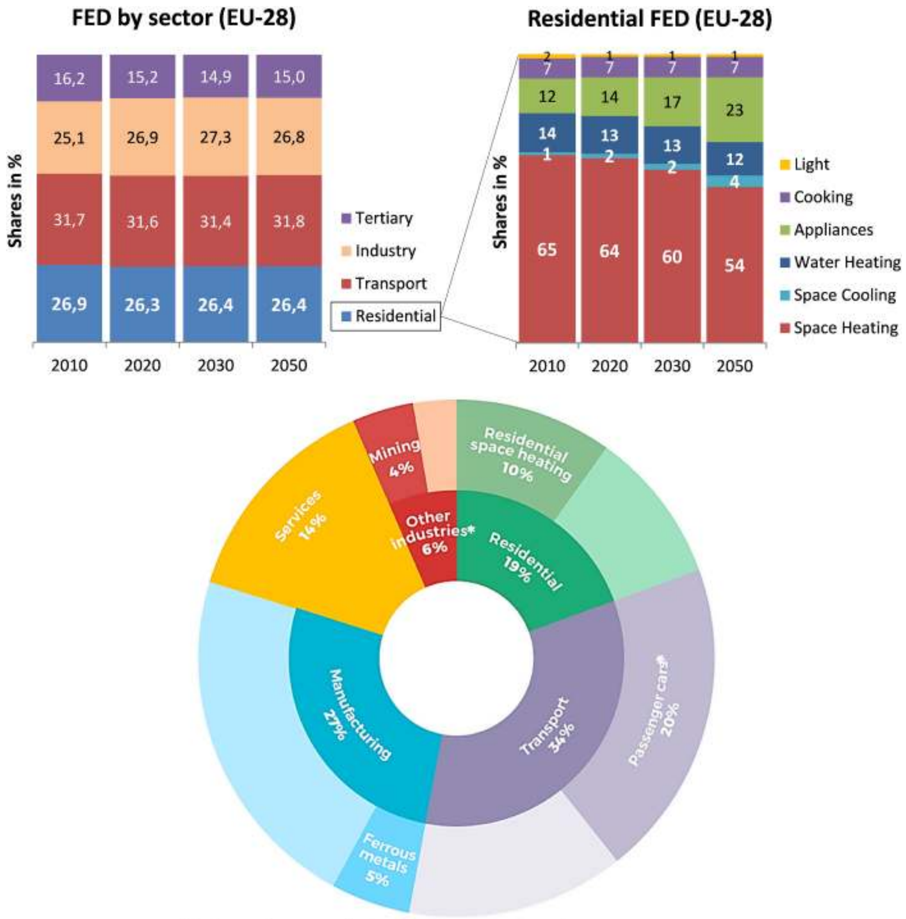
Thermal energy storage (TES) methods can be classified into three categories: thermochemical, latent, and sensible TES. Thereof, thermochemical TES is the only technology enabling long-term storage of thermal energy, since the underlying storage mechanisms are based on chemical ad- or absorption and are therefore almost free of energy losses in steady state [45,46]. However, the deployment of this technology for residential use is still in early development with few prototype set-ups, very high unit costs and no long-term operation experience. Thus, even though the technology is very promising due to a high energy storage density and its seasonal storage potential, it is not expected that thermochemical TES will play a major role in the residential sector in the short term.

2.1. Latent and sensible TES

Latent TES utilizes the latent heat of a phase change, thus the energy required to freeze or melt a given medium, to store thermal energy [47]. A huge variety of phase change material (PCM) (e.g. water, paraffin, salt hydrates) with a large diversity of melting temperatures and phase change enthalpy is available and can be utilized as latent TES. However, the application in residential buildings limits the amount of suitable PCMs distinctly due to the high restriction of melting temperatures, super-cooling effect, corrosive behavior, toxicity and costs [47]. Therefore, micro-encapsulated paraffin based PCM (e.g. integrated in gypsum boards or in slurries) or water based ice-storage methods are the most suitable latent TES for residential applications [48,49]. The amount of energy stored in latent TES is given by

$$Q_{latent} = \rho \cdot V \cdot L, \tag{1}$$

wherein ρ is the density, V the volume, and L the specific latent heat of the material.



*Other industries includes agriculture, mining and construction
Passenger cars includes cars, sport utility vehicles and personal trucks

Fig. 2. Top: Final energy demand (shares in %) in the European Union according to EU-28 trends from reference scenario 2010 to 2050 [7]. Bottom: For comparison, largest energy end uses in IEA countries 2014 (worldwide), ©OECD/IEA 2017 Energy Efficiency Indicators Database, IEA Publishing https://www.iea.org/newsroom/news/2017/december/the-iea-energy-efficiency-indicators-database.html. Category *energy end uses* corresponds to *final energy demand* in the top diagram and *services* correlate with the *tertiary* sector.

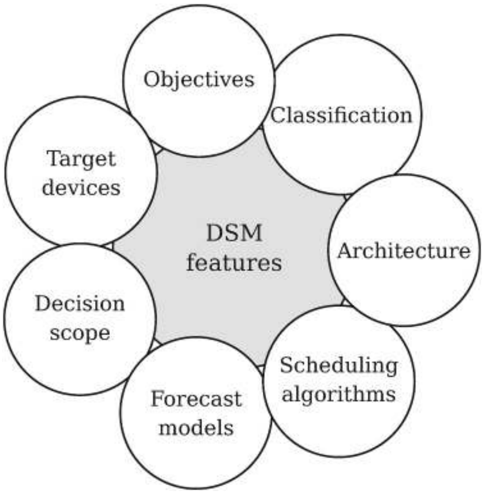


Fig. 3. Overview of the characterizing features of DSM concepts [67].

In sensible TES, the thermal energy is stored through changes of the temperature of the storage medium. The amount of stored energy is proportional to the allowed temperature range, the specific heat capacity, and the mass of the storage medium described by volume and density [47]. Therefore, the thermal energy stored by an ideal sensible TES can be described according to Eq. (2):

$$Q_{sens} = \rho \cdot V \cdot c \cdot dT, \tag{2}$$

wherein ρ is the density, V the volume, c the specific heat capacity and dT the temperature change of the observed material. For the application in residential buildings sensible water based hot and cold storage tanks, rocks, bricks, and the soil adjacent to the building can be used as TES [47,48]. Water-based storage tanks are the most widely used TES solutions in this sector, due to the high specific heat capacity, the natural stratification into thermal layers, the good controllability of heat transfer, and the easy integration with mostly water based residential heating systems [47].

2.2. *Thermal storage based residential load shifting*

Often the most visible appearance of residential DSM is active control of domestic "smart" appliances (e.g. washing machines, dryers or dishwashers) according to the availability of renewable energy. However, residential electrical appliances are responsible for a very small amount of the residential energy demand; therefore, these DSM measures have only limited load shifting (LS) potential [7,50,51]. While this might change in the future with an increasing dissemination of electric vehicles [51], the space heating and domestic hot water (DHW) requirements of residential buildings already make an essential share of the current German and European final energy demand (FED), as shown by Fig. 2. This yields theoretically large LS potentials. Early residential load shifting measures successfully utilized night storage heaters (NSH), which were operated according to static Time-of-Use (ToU) pricing, with significantly lower electricity costs during the night [52]. Furthermore, the LS potential of hot water storage tanks is often utilized in solar thermal systems to decouple generation and consumption times. Hot water tank based LS associated with heat pumps (HP) and resistance heaters has been evaluated in several studies but demonstrated limited potential and cost-effectiveness [51,53,54] to date. However, it has been shown that beyond these measures thermal demand side management in residential buildings has great potential to play a major role in stabilizing the future power grid [53,55,56].

It is an ongoing debate whether NSH with their low energy efficiency should play a role in future residential LS [52]. However, HP are already operating with dynamic external signals, which indicate shut-off periods during peak consumption times. The LS potential of HP is expected to be even higher [57]. Exemplary solutions for coupling heat pump operation with local PV generation are already available [58]. Residential heating systems do not only consume but also inject electricity into the grid when heat and power (CHP) units are combined. A grid-compatible operation of such systems is usually only possible if the electricity generation can be decoupled from the heat demand [59]. Therefore, most LS measures involving HPs and CHPs require thermal flexibility within a residential building. However, the current energy market conditions do not encourage any investment in thermal storage beyond the requirements of reliable and secure operation of the installed heating equipment [60]. The lack of motivation to engage in and invest in LS activities has been identified as a major risk to exploiting the residential flexibility potential, along with the slowly emerging metering and communication infrastructure required to receive DSM signals or Real-Time-Pricing (RTP) information [48,56,60].

3. Overview of demand side management

Demand side management (DSM) is generally defined as the modification of energy demand of consumers through different methods such as financial incentives. The main implementation mechanisms of DSM are short-term demand response (DR) and long-term energy efficiency programs. According to [61], DR is defined as "intentional electricity consumption pattern modifications by end-use customers that are intended to alter the timing, level of instantaneous demand, or total electricity consumption". Recently, home energy management systems (HEMS) have emerged for local load management at the consumer side. According to [41], HEMS are defined as residential DR tools that shift or curtail demand to improve the energy consumption and production profile of a building on behalf of a consumer by providing optimal operation schedules. Numerous sources provide in-depth reviews of HEMS or building energy management systems [41,62,63], scheduling in buildings [64,65], and DR concepts [50,66]. Accordingly, the characteristic features of DSM concepts are identified and illustrated in Fig. 3.

3.1. *Objectives for scheduling strategies*

The objectives for operation scheduling in HEMS vary depending on the consumer, the application, and the DR framework. The list includes:

- Energy cost reduction e.g. minimization of energy consumption.
- Increase of consumer comfort and well-being.
- Environmental concerns e.g. reduction of GHG emissions.
- Load profiling which evaluates the desirability of the load profile to some party such as:
  - Reducing grid dependency for consumers.
  - Reducing peak demand for utilities.
  - Adapting to the variations in power supply from renewable energy sources to reduce power imbalance (smart grid application).

3.2. *Target devices in DSM concepts*

According to the survey [41], the majority of HEMS and DR studies in the literature typically target electrical appliances or white goods such as time-shiftable loads, notably washing machines, dryers and dishwashers as well as electrical storage systems, mainly stationary batteries and electric vehicles. The scheduling of heating systems, aside from electrical heater has recently gained a lot of attention. The main idea is to exploit the thermal flexibilities enabled by the availability of thermal storage to allow for electrical load shifting.

3.3. *Approaches: decision scope*

HEMS can be classified into reactive and predictive approaches.

Table 1
Demonstration projects/field studies in Northern & Western Europe; Abbr.: IC – industrial consumer, HH – household; Ref. in Table 4.

Project Name	Location Project Partners	Project Size	Duration	Research Questions / Objectives	Target Devices	Load Shaping Goals	Platform / Configuration	Results / Outcomes
PowerMatching City	Hoogkerk (Groningen), Netherlands	P1: 25 HH P2: 45 HH	2008 - 2014	-Consumer awareness, acceptance, feedback, privacy	Prosumers (μ-CHP, PV)	RT balancing Load following	HW storage tanks (separate tap water and heating, 200l)	Monetary flexibility (€ per HH and year) Societal cost (DR ↔ grid capacity)
				Integrate more i-RES	HVAC (HP)		'Living Lab' environment	Power flexibility bandwidth (HP)
	DNV KEMA (PM) Enexis (DSO) Essent, Gasunie TNO, TU Delft, …	≈10 Mio €		1. Distribution network congestion 2. Test of virtual power plants (VPP) and aggregation concepts 3. Scalability of ICT 4. DR market integration (TC)	DHW storage SWA PEV		Home gateways **Power Matcher** SW / MAS Energy Dashboard in HH	Load following performance; VPP energy autonomy: -65% … -90% out, -14% … -21% out (simulation) Smart meters: 'big data' issue can be relaxed, aggregation possible
Couperus	The Hague Netherlands Stedin (DSO) Eneco (BRP) TNO, IBM, …	300 HH	2013 - 2016	Balancing wind farm Distribution network congestion Maintain user comfort	HVAC (GS-HP, DHW) Building thermal mass	Peak shaving RT balancing	GS-HP (1KW$_{el}$) **Power Matcher** SW / MAS, RF communication Well-insulated buildings, No monetary reward	94% imbalance reduction, meeting user comfort bounds Control power up to 21% of nameplate power
Your Energy Moment (YEM)	Breda, Zwolle	≈ 50 HH	2012 - 2015	Consumer behavior (participation, acceptance, fatigue,…)	PV (1.5 KW) HP heating	Load shifting Self-consumption	Central EMS Users: HEMS	DR-capable new EMS Up to 48% peak load reduction
	Netherlands			Demand responsiveness of loads	Smart washing machines		Smart meters	User load: -18% / +31% (high PV) 14% of washing cycles automated
	Enexis (DSO) …						Smart appliances	Barriers: Consumer incentives, Legacy appliances, tariffs
Linear	Genk, Belgium 20 partners: KU Leuven, VITO, Miele, SIEMENS, Gov. Flanders, …	≈250 HH 9.5 Mio €	2009 - 2014	Standardized DR device interfaces	SWA	Load smoothing	HEMS Home gateway Smart meters	Manual DR too invasive ⇒ response fatigue Flexibility measures (≤150 W/HH)
				Develop end user EMS Price responsiveness (DR level?) Balance wind forecast errors Smooth transformer load curves	TCL (EH, HP) PEV	RT balancing	Smart appliance controls Project remuneration (bonus / capacity fee)	Benefit potential for DR: 19 € /a /HH
EcoGrid EU	Isle of **Bornholm** Denmark 15 partners:	≈ 2000 HH ≈100 industrial consumers	2011 - 2015	Define RTP on imbalance (forecasts, wind power, demand)	HP, EH,	Load shifting RT balancing	HEMS (of different brands) Smart meters	Price responsiveness, customer involvement Power flexibility (up to -27% per hour)
	Energinet, Østkraft, Sintef, DTU, …	21 Mio €		Integrate DR flexibility in E-Market	PV generation		Nordic power market emulation (5 min cycle)	
Smart Grid Gotland	Gotland Sweden Vattenfall, ABB, KTH + …	≈ 260 HH + ≈ 20 industrial consumers ≈25 Mio €	2013 - (ongoing)	Cost-efficient integration of 50% wind by 2020 Balancing wind generation Grid stability (power quality) DR market integration	HVAC (EH, HP, DHW) Battery Storage	Load shifting	Smart grid control center, Substations Smart plugs (remote control) Smart meters; PLC and GPRS communication	Multi-stage recruitment process, 56 HH in control group Regulatory innovations needed

Table 2
Demonstration projects/field studies in Central Europe; Abbreviations: HH – household; Ref. in Table 4.

Project Name	Location Project Partners	Project Size	Duration	Research Questions / Objectives	Target Devices	Load Shaping Goals	Platform / Configuration	Results / Outcomes
Municipal Plants for DR	Switzerland Ministry BFE	≈1 GW load	2014 - 2016	Seasonal shifting and control power potentials of municipal plants?	Municipal Plants Sewage plants	Load shifting	Qualified firms sell flexibility on reserve market (transmission system operator TSO)	Control power estimate (largest 30 to 40 plants in CH): +100 MW, -200 MW for 1h
	InfraWatt, Ryser Ingenieure AG, Alpiq AG				Water supply Waste treatment		Tailored optimization / engineering	Seasonal load shift (summer - > winter) of waste incineration plants: 250GWh
Tiko	Switzerland Swiss Energy Solutions AG, Sonnen, EKS, Tobler	≈ 4500 HH	2012 - 2017	DR to provide ancillary services Integration of i-RES Test of VPP concept (aggregation, pooling, resource selection)	HVAC (HP, boiler)	Load shifting RT balancing	TSO ↔ Pooling operator ↔ HH Control Units (M-Box) Smart Meter (K-Box) Smartphone App 400 CHF rebate for 450 CHF/a cost	Own SW developed Available on commercial market Fast DR reaction times (15s) Next goal: aggregate 70’000 participants (≈70MW).
Nice Grid	Carros, France	2500 HH	2012 - 2016	Micro grid: Test islanding with black start from PV and battery	PV Gen 1.9 MW	Load shifting	DSO: Network Energy	Recruitment campaign; communication and visualization, show room
(part of EU FP7 GRID4EU)	10 partners including ERDF (DSO), EDF, ADEME, Alstom, Daikin	30 Mio €		Integrate all PV power Minimize stress on LV network Initiate and analyze consumer behavior change	Battery Storage (local+ community 250 kW) HVAC load Uncontrolled appliances		Manager tool Unique inverter technology for PV and battery storage Users: Energy Gateway Smart Meter (Linky) Special user tariffs	Statistics on PV forecast errors
E-Energy Project Cluster	Mannheim, Mülheim, Krefeld	E-Energy:	2009 - 2014	Advance energy turnaround through ICT technology	HVAC	Load reduction	E-DeMA / E-Energy Marketplace software	-3% …-10% loads shifted with ToU (2 / 5 steps), decreasing with duration
Modellstadt MA	Germany	8150 end users		Increase system-wide energy efficiency (focus on buildings)	refrigeration (residential, commercial)	Load smoothing	DR aggregator Users: Gateways GW1|2 for manual | automatic DR	Load elasticity with RTP (avg. -10.6%, max. -23.6%) depends on season, day, and time
eTelligence		≈ 140 Mio €		Investigate load shifting potential of fridges / domestic appliances	SWA		HEMS, Smart Start (SWA) Smartphone App	Barriers: Sound business models for flexibility?
E-DeMa	MVV Energie Siemens, Miele, … + Universities (Dortmund, Bochum, Duisburg)	E-DeMa: 657 HH 21.5 Mio €		Investigate price elasticity of consumers under randomized RTP Advance regulation → prosumers			Metering portal E-DeMa tariffs	Standardized data exchange between market players?
Modellversuch Flexibler Wärmestrom	Boxberg Baden-Württemberg Germany EnBW	101 HH	2015	Distribution grid congestion when integrating more i-RES Decreasing curtailment? Design new flexibility tariffs	HVAC HP, electrical storage heaters	Load shifting	Intelligent substations (LV distribution grid) Smart meters Unique billing scheme	Dynamic estimation and control of load simultaneity factor New billing procedure

Reactive HEMS typically use heuristics, i.e. knowledge based techniques, which approximate solutions based exclusively on certain prescribed rules for the actual system state, with no consideration of predictions. An example of this approach for energy management in residential buildings is provided in [68]. The development of heuristics requires extensive experience and knowledge about the considered system and exploits case-specific strategies that cannot be generalized for other systems. The main advantage of a well-designed heuristic is the low computational effort required for generating a good solution. Yet, powerful heuristics are difficult to derive for complex architectures including diverse components. However, reactive HEMS have been recently formulated as multi-agent systems (MAS). MAS are negotiation based frameworks characterized by a flexible and extensible architecture. A notable example is provided by the "PowerMatcher" model in [69].

Predictive HEMS incorporate forecasts for estimating states to provide an optimal schedule under future conditions. Predictive HEMS rely on a mathematical program or meta-heuristic for the scheduling model. Typically [70–73], predictive scheduling is implemented in a moving window framework, also referred to as sliding window, rolling or receding horizon algorithms. This framework is used to reduce computational effort and improve the schedule by updating the forecasts in a cyclic manner. This allows for reacting to disturbances depending on the rescheduling rate, which is a feature of reactive scheduling.

Through embedding forecasts, predictive HEMS and DR are expected to hold an advantage over classical reactive approaches for the accommodation of volatile RE especially in scenarios with a large share of renewable generation capacity.

3.4. Forecast models in predictive scheduling

Predictive HEMS or scheduling incorporates several forecasts as inputs. These include predictions of weather conditions e.g. solar irradiation and outdoor temperature, PV and wind power generation, occupancy, as well as energy consumption behavior, i.e. space heating, domestic hot water and electrical demand. Forecast models have been heavily investigated [74–76] and can be broadly grouped in:

- **Black box models** which are data driven formulated and require no knowledge about the physical characteristics of the system. These comprise regression and machine learning techniques as well as modified formulations i.e. adaptive and stochastic formulation. These models are widely used, e.g. [77]. The field of applications includes price, weather variables, PV generation, electrical and thermal demand prediction among many others.
- **White box models** which are based on detailed physical representation of a specific system [78]. This approach is exhaustively applied for predicting building thermal behavior, i.e., space heating demand or indoor air temperature.
- **Grey-box models** that represent an intermediate stage between white and black models and are typically applied to predict thermal behavior as well [79,80].

3.5. Scheduling algorithms

Many approaches have been proposed to schedule residential energy systems according to the survey [81]. These can be categorized into:

- **Mathematical optimization or programming:** linear programming (LP), quadratic programming (QP), dynamic programming (DP), mixed integer linear programming (MILP), mixed integer nonlinear programming (MINLP); decomposition techniques such as Lagrangian Relaxation (LR) or Lagrangian decomposition (LD), Benders decomposition and Dantzig-Wolfe decomposition (DWD) combined with the column generation algorithm; robust optimization and stochastic programming.
- **Meta-heuristic:** bio inspired evolutionary algorithms (EA), population based genetic algorithm (GA) and particle swarm optimization (PSO), trajectory based simulated annealing (SA) and taboo-search method (TSM).
- **Heuristics:** rule based or knowledge based techniques and priority listing.

3.6. Architecture of DSM strategies

The authors of [82,83] provide an overview of control and DR system architectures. The arrangements comprise centralized, decentralized, and hybrid or distributed architectures. In centralized architectures, the central component has access to all information. Theoretically, a centralized approach allows for achieving the best solution. However, the difficulty of this approach lies in application bottlenecks such as scalability, computation tractability, data privacy concerns and communication infrastructure. Decentralized architectures eliminate several disadvantages of a centralized approach at the cost of stability and optimality. In a decentralized architecture, the overall problem solution is decomposed into sub-systems without direct coupling between them. Hybrid or distributed architectures are formulated based on a trade-off between stability and information exchange. In non-hierarchical distributed architectures, subsystems with similar or conflicting goals interact directly with each other, in a cooperative or competitive manner. An example of a non-hierarchical distributed architecture is provided in [84], in which a game theory based scheduling model for residential DSM is applied. Hierarchical distributed architectures employ a multi-layer structure with a coordinator or aggregator entity which coordinates the negotiation across the subsystems. Hierarchical distributed structures are typically applied in MAS [12]. Further, they are well suited for mathematical optimization using decomposition methods such as LR and DWD [85].

4. Existing use cases of TES-based DSM

As the predictable base-load supply in the grid is replaced by more intermittent renewable energy (i-RES) and large-scale grid storage such as power-to-gas is still in the trial stage, the load control of flexible consumers (DSM, DR) is becoming increasingly important. Indeed, the statistical flexibility found in load profiles aggregated from many consumers such as P2H loads seems to form a custom-fit counterpart to the volatility of many small producers of renewable electricity. In this review, the frontier between research and large-scale field demonstration of TES-based DSM is explored: where do we see generalizable and scalable success stories, what are practically realizable contributions of demand flexibility to future grid performance, and which major barriers towards mass deployment are remaining?

Tables 1, 2 summarize 16 DR projects worldwide that include in-depth field-testing and demonstration of demand response. Our main focus is on Europe (11 projects); five projects were carried out elsewhere, in the United States (3), China (1), and Japan (1). A majority of DR projects are known from and have been summarized in reports by the International Energy Agency (IEA DSM Task 17 – Pilot Studies and Best Practices of Demand Flexibility in Households and Buildings [33]) or in the 2014 Case Book by the International Smart Grid Action Network (ISGAN) [86], which is part of a framework created within the IEA. In 2012, already, a report by the Dutch KEMA laboratories "Inventory and Analysis of Smart Grid Demonstration Projects" [87] included well over 100 such projects worldwide.

Our unique criteria of project selection are stated and justified as follows:

Narrow Technical Review Focus (DR + HVAC): One main focus is on TES in buildings (HVAC in the residential and tertiary sectors, including district heating networks or municipal plants) which are

Table 3

Demonstration projects/field studies in the USA and Pacific States; Abbreviations: HH – household; Ref. in Table 4.

Project Name	Location Project Partners	Project Size	Duration	Research Questions / Objectives	Target Devices	Load Shaping Goals	Platform / Configuration	Results / Outcomes
AEP Ohio gridSmart	USA (Ohio)	≈ 250 HH	2013 - 2014?	Energy efficiency, CO_2 emissions	HVAC (cooling)	Load Reduction Load smoothing	Supplier: TC-DA market	3 consumer satisfaction surveys
	Supplier AEP Ohio, US-DOE,			RTP demo for DR using TC Improve power flow in distribution circuits		RT balancing	User: DA-capable HEMS, Smart meters	HH electricity bills -5% HH fatigue (thermostat overrides)
	Battelle / PNNL PJM, PUCO						Smart thermostats Capacity incentive	Wholesale electricity price -5% Max feeder load -10% Rebound peaks observed
Pacific Northwest Smart Grid Demo	USA (Oregon, Idaho Montana, Wyoming, Washington)	≈ 60000 HH 9 utility companies	2009 - 2013	Quantify SG costs and benefits Use open standard for automated DR (OpenADR)	All building loads (residential and commercial)	Load smoothing	TC architecture, transactive nodes	TC reference implementation (large scale) Statistics on user response
(PNW SGD)					Cooling (AC), AHU / Fans Battery storage	RT balancing	IBM-ICS Internet scale control system middleware Users: Programmable Communicating Thermostats PCT Custom HEMS for TC (IBM)	Annualized DR equipment costs System-wide costs ↔ load reduction levels -8% peak load (RTP simulations) Congestion mitigation not successful
	US-DOE			Evaluate and increase demand responsiveness				
	Battelle / PNNL +12 utilities	179 Mio US$		RTP demo for DR using TC Integrate i-RES (wind): 0, 10, 30%				
Olympic Peninsula Demonstration Project (OlyPen)	USA (Washington)	112 HH	2004 - 2007	Improve power flow in distribution circuits; Reduce feeder overload	EWH, SWA, TCL, HVAC (commercial building)	Load smoothing	TC / RTP implementation	TC pilot implementation
	PNNL			Test islanding mode (Diesel gen.)			IBM-ICS Internet scale control system middleware	Customer recruitment
				RTP demo for DR using TC	Municipal water pumps (150 KW) Diesel generators (600, 175 KW)		Users: PCTs Rewards / incentives; 'shadow market'	Load responsiveness comparison between ToU, CPP, RTP, and control group. TC / RTP triggers diurnal load shifts and bounds feeder load (to 750 KW) for one year!
Kitakyushu Smart Community Creation Project	Kitakyushu Kyushu Island	≈ 200 residents ≈ 50 companies	2010 - 2015	Stabilize PV and wind integration (reverse power flow, voltage rise)	HVAC Home appliances, Lighting	Load reduction	EMS Hierarchy (Community CEMS → BEMS →HEMS)	-20% peak load reduction with ToU (at peak price level) RTP for load balancing to be reviewed
						Load Shifting	Smart meters Manual DR Program Incentives above RTP	Analysis of new business cases needed
	Japan Kitakyushu Smart Community Council	Multi - Energy grid (+heat, gas, H_2, Fuel Cells) 16.3 bn. Yen ≙ ≈ 126 Mio €		DR goals (residential & industrial): 50% CO_2 reduction 20% Energy saving 15% Load Shifting	PEV charging Solar PV Storage Battery			
Shanghai Project	Shanghai China	33 buildings (comm.& public) 31 industrial plants (100MW load)	2014	Reduce peak load (top 60 of 1200 GW)	HVAC (summer cooling)	Energy conservation	DR control architecture:	New baseline load calculation method
				Coordinate existing load management programs	EWH Lighting	Peak shaving Load smoothing	DR center → Aggregators → User sub-metering Subsidy per KW curtailed load	-10% … -15% peak load shaving (short trial periods) Amounts and types of incentives are insufficient
	> 8 partners (Ministries, SGCC, NARI, Shanghai Univ.)			Collect customer feedback Investigate market incentives Enable policy research towards efficient electricity markets	Elevators		Platform / technology details unknown (using OpenADR)	

electrically operated in large numbers. Their electricity consumption is controllable, individually or aggregated, as a flexible resource (demand response, active demand). In addition to this core requirement, further household appliances like washing machines (‘smart wet appliances’, SWA) or electric vehicles (PEV) may be investigated.

Vertical Impact Analysis: A thorough empirical impact analysis of this narrow subject covering several integration levels should accompany the field testing, from

- End-user requirements and experience (user acceptance and involvement, load responsiveness, permanence, comfort, economy, autonomy, privacy), to
- New terminal devices becoming part of the SG automation hierarchy (advanced metering, programmable thermostats, smart starting function, DR-capable or grid-friendly HEMS), to
- Core control and coordination methods (balancing, load scheduling and dispatching, forecasting, and pricing) at the distribution and transmission grid levels and on different time scales, to
- Measurable grid-level performance impacts, such as practically achievable potentials of shifted or leveled load or frequency reserve, and benefits on supply reliability, power quality, loading of distribution networks, electricity costs, or sustainability of the power generation mix.
- The interplay with the smart grid economy (pricing, new tariffs, regulation, new stakeholders and business models) and with parallel streams of innovation (e.g. emerging standards on ICT, automation and control, IoT and vulnerability) are crucial aspects of the analysis.

Field tests accompanying the introduction of new technologies, products, or devices such as Smart Meters, Smart Home Appliances, or innovative components for grid modernization often lack the analytical and scientific focus described and are discarded.

Readiness Level: With regard to the technology road map, pilot projects include not only innovative grid and ICT hardware (HW) and software (SW), but also a significant number of real electricity customers/households that cover their everyday electricity demand thereon. At the same time, pilots should provide unique degrees of freedom to test and compare new regulations, tariffs, and role models, not alone methods or algorithms. We investigate use cases on a fine line between shielded laboratory environments denoted often micro-grid demonstration sites (see Table 1 in [88]), and (pre-) commercial roll-out programs. The latter are tied often to a specific supplier or utility and always act within an existing regulatory framework and market structure, for example, to explore a new suite of DR tariffs of which Paterakis et al. [30] present an impressive variety. Whereas laboratory-scale micro-grids exclude real customers and are partly based on simulation, the roll-out programs are too narrow in scope and lack the openness to provide insight into a different energy future. We admit a conflict of goals making it difficult to find projects that perfectly fit on that line and will discuss our reasoning further below.

Project Period: Most field demonstration projects reviewed started after 2010 and ended before 2016, but a few started before or are still ongoing.

4.1. Project categories

The project categories represented by the columns in Table 1–3 are explained briefly unless their meaning is obvious. The respective project references are given in Table 4.

Project Size (C2): Several independent size indicators exist, and the easiest available data were adopted. The number of participant households is most informative, but in some cases the total load (MW or GW) is specified instead. Total load and participant numbers are not readily convertible because average household loads vary between countries and projects, and in one case a few large municipal plants are the DR providers instead of many small residential customers. Another criterion is project cost or funding, but for large project clusters the costs are not always attributable to the field tests properly.

Research questions/objectives (C3): The project research questions substantiate the desired impact analysis mentioned before. Objectives either focus on the consumers, when their active cooperation is voluntary but essential for the project success, or emphasize the integration issues with regard to ICT standards or existing DR market or regulatory frameworks, or focus on performance variables measuring the grid benefit. Hosting more i-RES, improved balancing despite uncertainties, new DR contributions to frequency reserve (power quality), improved spatio-temporal patterns of line or transformer loading (average-to-peak load), or achievable potentials of load flexibility are important quantifiable benefits. New coordination or scheduling methods as discussed in Section 3 have not been targeted by all projects. Research objectives may include also non-functional goals.

Target devices (C4): The device/TES configurations most suitable for load management were introduced in Section 2. Those addressed primarily in the field tests are abbreviated in column 6; please refer to the list of acronyms. HVAC applications rank first and other, e.g. deferrable, household appliances second. Households able to feed electricity (back) into the grid, such as batteries, PEV, co-generation units (CHP), or PV generation are denoted as “prosumers”, and in some cases their power ratings are specified.

Load shaping goals (C5): According to Gelling's classification [89], contributions from the demand side can reduce or increase the overall load level (e.g. through energy saving or increased electrification due to vehicle-to-grid (V2G) or heat pumps), or target specific load shapes/profiles (of individuals or aggregations), such as shifting or leveling load patterns over a given time window (peak shaving, valley filling). In addition to such scheduled services, canceling suddenly arising residual load or following a frequency signal in real time have become key applications of domestic DR [9].

Research Platform/Configuration (C6): This category covers the experimental concepts and components of HW, SW, organization, and architecture, which define the field testing infrastructure. The hardware and software includes metering, device control (smart thermostats, smart start functions), visualization, new HEMS software, architectural frameworks, and communication protocols. Organizational concepts concern the market (pricing schemes, tariffs), the additional rewards or incentives for participants, new regulatory specifications for running experiments, or new roles and institutions like demand aggregators placed between grid operators, utility companies, and consumers.

Results/Outcomes (C7): The technical results summarized in this column provide direct answers to the research questions in column 5 or mention spin-off results obtained in the project, as well as general lessons learned. Question marks indicate new research questions raised

Table 4
Project references table.

Project name	Refs.
PowerMatching City	[33,69,90–95]
Couperus	[33,95,96]
Your Energy Moment (YEM)	[33,94]
Linear	[33,97–101]
EcoGrid EU	[33,102–106]
Smart Grid Gotland	[107–109]
Municipal Plants for DR	[110]
Tiko	[111]
Nice Grid	[86,112,113]
E-Energy Project Cluster	[17,33,114–116]
Modellversuch Flexibler Wärmestrom	[117]
AEP Ohio gridSmart	[118]
Pacific Northwest Smart Grid Demo (PNW SGD)	[119–124]
Olympic Peninsula Demonstration Project (OlyPen)	[125,126]
Kitakyushu Smart Community Creation Project	[86,127–129]
Shanghai Project	[30,130–132]

Table 5
Technology matrix of selected field studies.

Project	Operational Variables	DR Time Scale	Decision Scope	Decision Algorithm	Architecture	DR Automation Degree	DR Control
PowerMatching City	User: Thermal comfort, electricity cost Grid: Distribution network utilization Locational marginal price (LMP)	RT Balancing (5 min)	Reactive	Optimization (RT Market Clearing)	HD / Bi-direct	Automatic	Indirect-RTT
Couperus	User: Thermal comfort Aggregator Balancing Cost Substation / Transformer loading Residual power	RT Balancing / Load smoothing (5 min)	Reactive	Optimization (RT Market)	BRP ↔ Aggr: HD / Bi-direct Aggr ↔ User: C / Uni-direct	Automatic	User: Direct-LC Aggregator: Indirect-RTT
Your Energy Moment (YEM)	User: Electricity cost Locality of generation & consumption	Strategic + Schedule (Day-ahead)	Reactive	Heuristic	C / Bi-direct	Semi-Automatic, Overrule	User: Indirect - ToU
Linear	User: Price Responsiveness, monetary benefit Grid: Residual power, Flexibility (GW, hrs of time shift) Transformer load profiles; Feeder voltage profiles Transformer Age & Load distribution	Schedule (Day-ahead, intra-day)	Predictive	Stochastic optimization ILP	HD / Bi-direct	Manual + Automatic	User: Indirect - ToU Direct-LC
EcoGrid EU	User: Price Responsiveness Grid: Residual power (imbalance) Market price curves	Schedule (Day-ahead) + RT Balancing / Load smoothing (5 min)	Predictive	Quadratic Optimization Bidless RT market	HD / Uni-direct	Manual +Automatic	Aggregated Users - Direct-LC Other Users: Indirect - RTP
Smart Grid Gotland	User: Thermal comfort, electricity cost, satisfaction, Load shifting potentials, Temperature-corrected load Grid: Residual power, Power quality, Wind integration level, Supply interruption statistics (SAIDI)	Schedule (Day-ahead)	n/a	n/a	n/a	Semi-Automatic with Overrule	Direct - LC Indirect - ToU
AEP Ohio gridSmart	User: Load Sensitivity to RTP Distribution network: Power densities, LMP, Supply interruption statistics (SAIDI) Societal: Pollutant & GHG emissions of generation	Strategic RT (down regulation)	Reactive	Optimization (RT double-auction market)	HD / Bi-direct	Semi-Automatic with Overrule	Indirect - RTT
Pacific Northwest (PNW SGD)	Transmission and Distribution network: i-RES integration level, Generation statistics Load variations (temporal, spatial) Supply interruption statistics	Strategic RT (Balancing / Load smoothing)	Reactive + Predictive	Optimization (RT market)	HD / Bi-direct	Automatic	Indirect - RTT
Olympic Peninsula (OlyPen)	Distribution network: Feeder load, temperature variations Real-time price curves	RT (Load smoothing)	Reactive	Optimization (RT market)	HD / Bi-direct	Semi-Automatic with Overrule	Direct - LC Indirect- ToU, CPP, RTT
Nice Grid	Micro Grid KPIs: User statistics (opting out), Load amounts shifted or shed i-RES integration level, PV forecasting errors Voltage deviation (LV network)	Schedule (day-ahead, intra-day) RT (congestion)	Predictive	n/a	HD / Bi-direct	Manual	Indirect - Alert
E-Energy	User: Price Responsiveness Load shifting potentials	Schedule (day-ahead, intra-day)	n/a	n/a	n/a	Manual + Automatic	Indirect - ToU, CPP, RTP

or possible barriers seen on the road towards mass participation of HVAC/DR as flexible loads.

4.2. Project technologies

The decision and control technology implemented for DR is characterized in more detail by the technology matrix given in Table 5. Due to the lack of published information, Table 5 includes only a subset of eight demonstration projects. It should be noted that some demonstration projects have stipulated independent scientific work in unit commitment, dispatching, or decision making; but it is not clear whether the methods proposed or functions implemented belong to the core system under field test. The technology-relevant categories represented in the columns in Table 5 are as follows.

Operational Variables (C2): The Objectives (column 5 in Tables 1, 2) are substantiated with those functional goals and variables that express the physical grid states or the interests of individual stakeholders or the public, such as environmentally-friendly power generation. Goals addressed by scheduling were discussed in Section 3.1. In addition, quantitative performance measures are included that were not explicitly targeted (controlled or optimized) by the grid system under test but were monitored externally to evaluate the impact of DR strategies. Project results exist in the form of time series or aggregated statistics, e.g. probability densities.

DR Time Scale (C3): The load changes envisaged by DR (column 7 in Tables 1, 2) are characterized as strategic (e.g. energy conservation, preferring local use of locally generated electricity), or as scheduled (when DR affects a day-ahead or intra-day load schedule), or as RT, when DR reacts to unforeseen situations in real time, such as RT balancing, load following, or frequency response.

Decision Scope (C4): Decisions concerning only the actual system state are classified as reactive according to the taxonomy in Section 3.3, and otherwise as predictive. Having distinct decision scopes at different levels is possible. For instance, an EMS at household level could incorporate predictions of weather and storage temperatures in its price bid, whereas the market agent looks only at the current bids to find the clearing price.

Decision Algorithm (C5): According to Section 3.5 the decision making and especially load scheduling algorithms are classified into methods of mathematical optimization (which may still be reactive or predictive, using only actual states or state predictions), and into simpler methods based on heuristic rules or on meta-heuristics for seeking global optima of decision variables.

Architecture (C6): In Section 3.6 the information architecture in which DR strategies are implemented has been characterized as central (C), decentralized (D), or as hierarchically-distributed multi-layer architecture (HD). Independently, the essential information flow between components on the same layer or between adjacent ones is characterized as unidirectional, bidirectional, or multi-cast.

DR Automation Degree (C7): This is essential when human consumers are part of a closed control loop. Under manual DR consumers retain their autonomy to start or delay appliances, notwithstanding prices or other incentives. A DR strategy is automatic if appliances are controlled directly (remotely) or indirectly through a software agent acting on dynamic prices. Semi-automatic strategies take a middle course by offering the consumers preferences to strike a balance between thermal comfort and economy. The loads are dispatched automatically in accordance with the preferences. Often, users may overrule automatic decisions.

DSM Control (C8): A common dichotomy distinguishes direct load control (DLC) of appliance states from indirect control via prices [30,81]. DLC in the present review means controlling appliances' load states physically without recourse to economy (prices, scarcity). The control algorithms can address consumers individually by switching device states or changing thermostat set points or modifying power levels (if the appliance permits), or collectively by specifying switching probabilities or random delays [133,134]. In any case, DLC entails independent contractual payments to incentivize or remunerate the flexibility provided as a service. With indirect control, on the other hand, the electricity price (€/kW) conveys all information about the grid state and the direction of flexibility desired. Time-integrating price and consumption (kW) yields the costs; therefore, the cash-flow is by means of an energy tariff. In Table 5, this case is distinguished further by the type of pricing:

- **Time-of-Use** (ToU): prices are priorly known by the time at each day;
- **Critical-Peak-Pricing** (CPP): prices signal the current load situation but are announced ahead;
- **Real-Time-Pricing** (RTP): prices signal the current load situation but are set without notice and unilaterally by the utility company or grid operator.
- **Real-Time Trading** (RTT): as RTP, but prices are negotiated among all buyers and sellers at a common market (in two stages, placing bids first and then clearing the market).

Where mutually exclusive entries appear together in Table 5, such as both "manual" and "automatic" activation in column 7, both alternatives were field-tested at different project stages, or different consumer groups were compared using different control mechanisms.

4.3. Summary of demonstration projects

With respect to strategic focus and technology, the projects arranged geographically in Tables 1–3 can be divided into three (overlapping) groups:

- **Group 1** focuses on the real-time electricity market as a key technology for power balancing and coordination and on its implementation and field testing in an existing regulatory environment. Five large projects implemented a negotiation scheme with bidding and market clearing "in real time" (denoted transactive control (TC) in the USA): OlyPen, PNW SGDP, AEP Ohio GridSmart, Power Matching City, and Couperus. In a sixth project (EcoGrid EU) a bid-less algorithm was implemented that determines the price unilaterally from behavioral predictions of market players. Therefore, "indirect" control strategies (in column 8 in Table 5) using the real time price (RTT, RTP) are dominantly represented in this group.
- **Group 2** is concerned mainly with the users (residential consumers or prosumers) and the interfaces for integrating their appliances into the SG as flexible loads. Subject matters include consumer motivation and sustained involvement, price responsiveness, using home energy management systems (HEMS), data privacy and security, and long-term impact of DR on electricity bills (PM City, YEM, Linear, EcoGrid EU, SG Gotland, E-Energy, Nice Grid). This consumer focus is often motivated by the development and demonstration of self-sufficient energy communities, virtual power plants or micro-grid cells.
- **Group 3** is most interested in the measurable benefits of TES-based DR for future distribution grids, e.g. practically achievable potentials of load shifting, integrating higher levels of i-RES, improving the power quality, and mitigating congestion problems in distribution circuits. Projects with this focus include Municipal Plants, Tiko, Flexibler Wärmestrom, the Chinese Shanghai Project, and the Japanese Kitakyushu project. Most projects from group 1 and several from group 2 analyzed the grid benefits as well.

Notably, those field demonstration projects that are explicit about new coordination methods for flexible demand (especially TES-based) and also put these high on their testing agenda (group 1) rely on TC, where we view the bid-less method of EcoGrid EU as an alternative form of market-based control. From several large projects, such as Chinese Shanghai, Japanese Kitakyushu, Swedish Smart Grid Gotland or French Nice Grid we could not find sufficiently reliable details, especially on the algorithms for balancing and dispatching. Several projects from group 2 simply pass on the dynamic electricity tariffs (ToU, CPP, or RTP) available in some DR programs to their test customers. A notable exception is the E-DeMa sub-project of the German E-Energy cluster where a new electronic market place [116] has been designed, implemented, and field-tested. The core efforts in E-DeMa however went into the architecture and ICT framework and not into specific market algorithms as was the case in the PM City or the PNW SGD project.

Finding the market-based TC so strongly represented in the largest pilot studies without specifically searching for it did come as a surprise, because mass deployment of small-scale TES storage for flexibility must solve so many problems in different areas and must invoke diverse methods. For this reason, the TC methodology, its virtues, restrictions, and simplifications are reviewed in some detail.

4.4. Transactive Control

Transactive Control (TC) has been implemented and field-tested in the Olympic Peninsula Demonstration Project (OlyPen, the first project of this type), the Pacific Northwest Smart Grid Demo (PNW SGD), AEP Ohio gridSmart, and in Europe the PM City and the Couperus projects.

At the core of TC lies a real-time electricity market that balances load and generation in real-time (periodically, every five minutes) and decides on the units' dispatching order. At the beginning of the current period all pending bids for power generation or consumption are collected. An auctioneering algorithm then aggregates the buyers', respectively, sellers' bids - each bid comprises a power level and a price - into two bid functions. The algorithm then finds their intersection as the price that cancels supply and demand amounts, and sends the cleared price back to the bidders (Fig. 4). Demand bids above and supply bids below the clearing price succeed and contract here all at the same clearing price.

A supplier bid curve can be imagined as a merit-order function: the bids are ordered by increasing prices and their offered power "packets" are stacked in that order. Price steps correspond to the marginal costs of the cheapest remaining generator that can supply additional power. The demand bid curve is aggregated similarly from demand bids ordered by decreasing prices. A consumer signals urgency of power needs by the price he/she is ready to pay: for instance, the closer the temperature or filling level of a P2H application comes to its tolerance limits, the higher the acceptable price. Demand bid prices are often piecewise linear transformations of the thermal goal variables that indicate the quality of service. The function parameters (slopes and offsets) may reflect a trade-off between comfort and energy made internally [91,125,124]. Demand bid curves for deferrable loads can be constructed similarly as a piecewise linear transformation of starting time such that the price becomes maximal at the latest optimal starting time [135].

As shown through the bidding examples in Fig. 4, TC is a general method for real-time balancing that copes with generation, flexible demand, and storage resources. Any demand that is not basically excluded from flexibility – such as plug loads, possibly – must place a bid at a competitive market and await the clearing price before proceeding; i.e., demand is flexible and is granted conditionally by design. Power and reserve power are treated and traded equally as a substitutable flow commodity. Locational constraints such as the capacity of a transmission line or a transformer in a distribution circuit can be accommodated: at the level of power injection that would break the constraint, the bidding price normally indicating marginal generator cost would rocket up, to infinity in the worst case. To update these

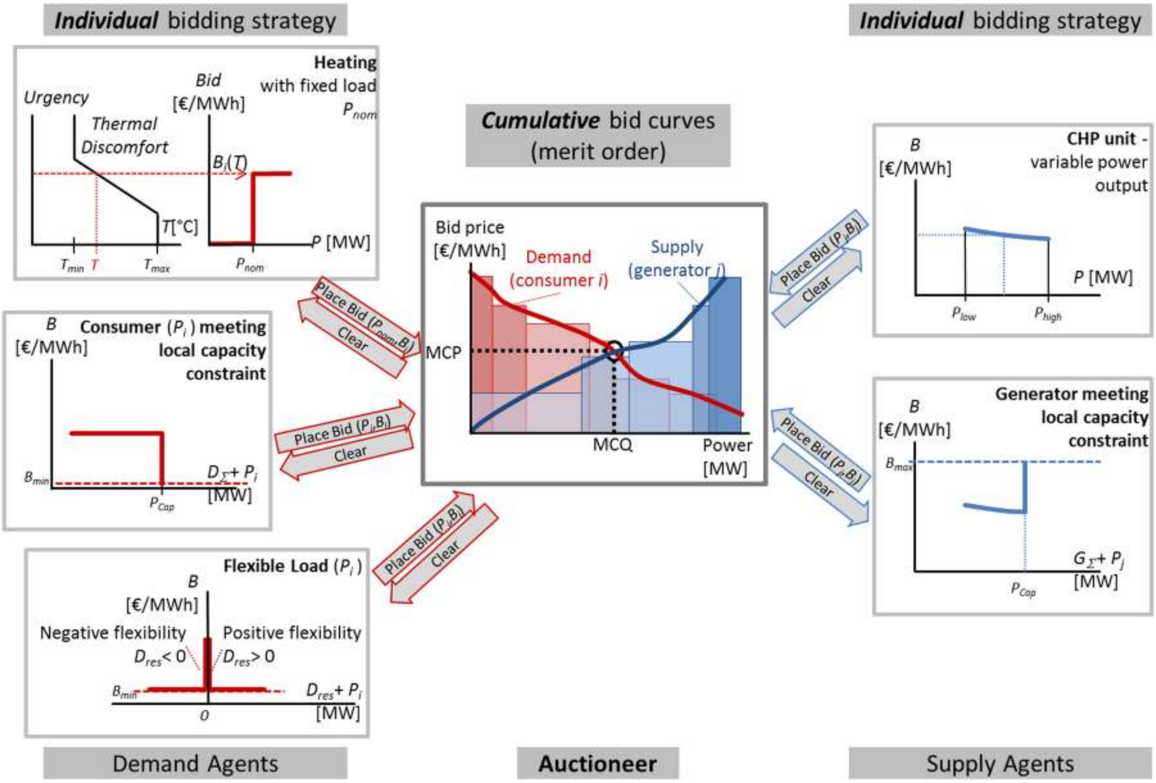


Fig. 4. Microeconomic power balancing through negotiated real-time prices (RTP): On the left and right are shown individual bids for power demand, respectively, power supply, together with bidding strategies for special cases such as flexible demand and capacity constraints (see text). The auctioneering process in the center sorts the bids by descending price order into an aggregated demand curve, respectively, by ascending price order into an aggregated supply curve. Their intersection point (assumed existing and unique) defines the market clearing quantity (MCQ) and price (MCP).

constraints incremental power flow calculations (assuming balanced conditions) are performed concurrently with the bidding functions. Residual load, i.e. a sudden gap opening between demand and supply due to forecasting errors, is closed in the same way by a modified supplier curve: with negative residual power the price becomes zero (→ "consume at any price") and with positive infinite (→ "consume by no price").

The basic TC scheme neither uses nor provides load schedules for planning the future and therefore is seen as a reactive mechanism according to Section 3.3 (column 4 in Table 5). However, in actual field implementations such as PNW SGD, predictions built on forecasts are combined or blended with the real-time dispatch (TC) algorithm [119,123].

The DSM control type is tagged Indirect - RTT because the negotiated price alone defines the threshold above which loads will be up and running. When market clearing is found by simple intersection of merit-order-type bid curves, the decision-making is classified as heuristic (column 5 in Table 5). More complex optimization algorithms for the clearing decision are however possible and are compatible with TC [121]. The architectures for implementing TC are classified as hierarchically-distributed: the auctioneer on top communicates bi-directionally with the bidders at the leaves (tag HD/bi-direct). In a full-fledged distribution grid, this basic hierarchical relation may be repeated at several layers or combined with different architectures at the leaves or on top.

A comprehensive in-depth presentation of TC and its realization in a multi-agent architecture is found in Kok's PhD thesis [91]. Detailed implementation reports and case studies, e.g. on how to compute and parametrize bidding functions for flexible loads, are available for the OlyPen demonstration project [125,126], for PNW SGD [123], and for the AEP Ohio SG project [118]. Several thematic and methodical surveys on TC provide insights how to optimize more complex goal functions and handle ancillary constraints [95,121,136] on top of the RTP-controlled dispatch. Hu et al. [95] modify a preferred schedule for charging electric vehicles (PEV) by incorporating locational capacity constraints of the distribution circuit. Chassin at al. [136] provide guidelines to determine the regulation price of grid-friendly household appliances.

4.5. Significance of field test results

All demonstration projects reviewed successfully implemented and carried out their research program. In several field tests quantitative performance figures were measured:

- DR potentials, specified as a percentage of individual or aggregate loads shifted or leveled, range between about 10% (3–10% in E-Energy, 8% in PNW SGD in a simulation assuming 30% of loads being responsive) and 48% of aggregate peak load in YEM. The majority of the load shares moved lie in the range 15–25%. These results cover the whole range of DR control options and pricing schemes (manual and automatic DR, ToU, CPP, and RTP tariffs, as well as TC-based RTT schemes). No evident correlation between load control performances and specific coordination and incentivization mechanisms was established. According to the PNW SGD study, work remains to be done on whether to use the RTP signals as a dynamic tariff for mass deployment of DR [123].
- Findings on the economic or societal impacts of DR and on the changes in consumption behavior were made mostly in the aforementioned Group 2 projects. Among these, only PM City reported comparative flexibility cost scenarios carried out at a national scale (in the Netherlands [33]): flexible demand and active distribution management were compared to investments in the network capacity (grid reinforcement).

  For raising customer awareness dynamic tariffs are mostly used but explicit messages or traffic lights signaling the grid state are also possible (e.g. Nice Grid). Effects on the electricity bills were analyzed in several projects; AEP Ohio GridSmart found moderate savings in household (-5%) and in wholesale electricity costs (-5%). Consumer acceptance, responsiveness, and price elasticity of loads were measured notably in YEM and in E-Energy. Consumer responsiveness varies over time, because it must be learned and may be unlearned due to fatigue or disinterest e.g. [137].
- Most clearly demonstrated were the benefits achieved for the distribution grid through flexible management of HVAC loads, especially by using TC technology (projects in Group 1). Imbalances due to fluctuating wind generation were reduced by up to 60% in PM City and up to 94% in Couperus. Through active load management, the loading of feeder circuits and transformers (substations) was persistently kept bounded within their capacity limits in several projects. Peak loads were reduced by at least 30%, and congestion was mitigated.

We do not further process or visualize the quantitative performance figures that are listed in Tables 1, 2, or even attempt to rank them, because they are incomparable between different projects. The precise meanings of goal variables differ. For instance, does imbalance reduction through DR refer to the total or the average power imbalance (MW), or to the number of DR requests made, or to some default balancing method, and what is the balancing period? Experimental conditions differ; for example, the available control power (in % of the load shifted) is a function of the number of households, the appliance types targeted and their simultaneity factor. Seasonal and weather conditions (wind) and load types further influence the imbalance reduction. There exist no standardized test cases or benchmarks.

Summarizing, we see the stress tests for mass deployment of TES-based flexible loads yet to come. The scenarios tested so far have limited relevance for, say, future penetration levels of 80% i-RES:

1. Doubts persist on the concepts of price elasticity and load responsiveness and how to measure them. These concepts are well-defined if people determine their own electricity consumption depending on real price signals (manual DR). Signals from the grid to the demand side can effectively control the physical grid states (balancing and loading), or can indicate economic scarcity in the grid (supply and demand), or can signal the customers a real financial burden, but these are generally different things. Customers' electricity bills and market prices according to the RTP curve often diverge in the field tests. Separate incentives were sometimes granted to motivate more customers to participate, or shadow markets were established. Still, load responsiveness is crucial and cannot be foregone as long as humans remain in the decision loop.
2. Flexible demand services on fast time scales providing frequency or contingency response or fast balancing were ignored in most field tests except Tiko [111]. Even the transactive markets apparently were not employed to provide ancillary services at the fast rate they were able to clear (every 5 min). In fact, the top-down control through a stream of price signals caused daily load shifting patterns that local HEMS might plan decentrally for themselves [125].
3. The majority of field tests (except PNW SGD, EcoGrid EU, Nice Grid, and Tiko) included a few hundred households or less as proper participants, which are too few to create a diverse load distribution and an environment for testing resource competition. Sometimes, the recruited households were too similar with regard to building types, HVAC equipment, load types and sizes (e.g. in the Couperus, Nice Grid, and Smart Grid Gotland project environments).[7]
4. Even the largest and most elaborated demonstration projects

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[7] These projects aimed specifically at creating self-sufficient energy communities, which tend to be more homogeneous than grown city districts. Still, the results do not permit general conclusions.

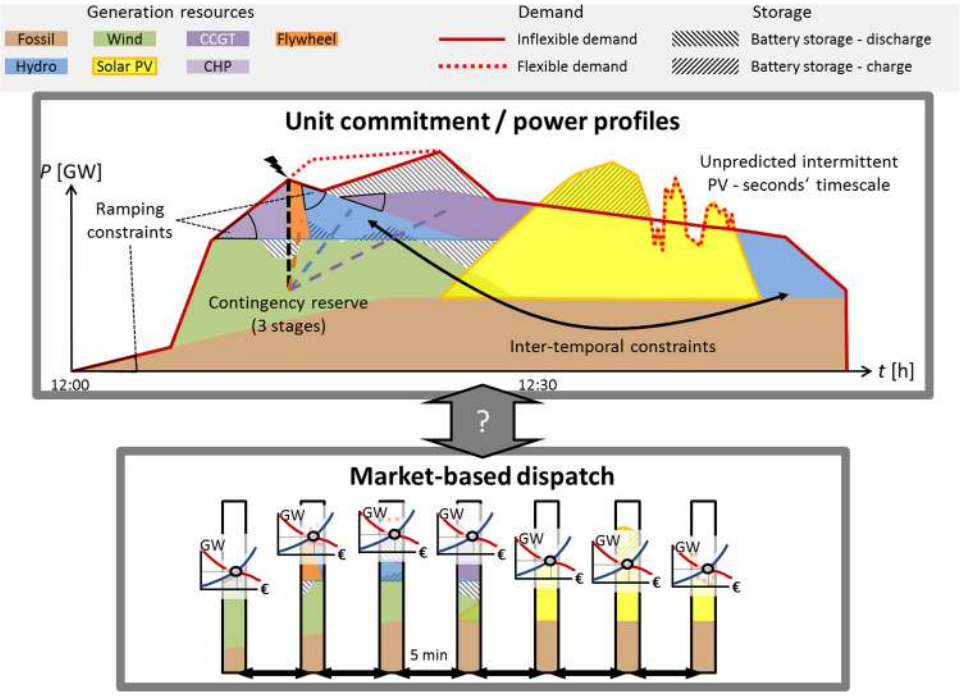

Fig. 5. Top: Example of a unit commitment problem illustrated in the time domain for different types of generators, storage, and demand, which must cope with inter-temporal constraints, ramping constraints, contingencies, and forecasting errors. Bottom: the same problem conceived as a snapshot sequence of independent market equilibria between demand and supply (RTP cleared every 5 min using the substitutable flow commodity paradigm).

suffered minor technical limitations, which highlight the difficulties of a pilot implementation compared to a simulation. In PNW SGD [123] flexible appliances can only drop or postpone load, i.e. provide positive balancing power. The reaction of flexible loads to prices was not field-tested in a closed loop but simulated, because third-party software did not permit the TC system reacting on prices to alter the load dispatching order ([123], pp.158). Based on the project reports, we cannot judge whether this limitation produced any noticeable quantitative effects.

On the other hand, the open-loop bid-less market algorithm proposed for EcoGrid [105] used no direct feedback from the end users but predicted their responses to real-time prices. Inaccurate forecasts by the rather complex algorithm could cause instability. We do not know whether the algorithm [105] or a simpler one was part of the field tests.

5. A challenging situation of grid balancing that heavily depended on a rich offer of flexible load has not been reported from the field trials. The particularly high balancing reduction of 94% achieved in Couperus may in part result from a down-scaled wind turbine generation. It would be informative to see how the basic RTP market scheme handled tight competition and dynamic inter-temporal constraints of flexible demand resources.

5. Critical review

Achieving permanently balanced and efficient allocation of grid resources is crucial for grid stability, supply security, and cost effectiveness of any electricity system [138]. In solving this problem control-theoretic and micro-economic concepts flow together [69,81,95]. Optimal control methods including predictive scheduling address the physical grid stability (frequency control, real-time balancing) and include economic costs as decision variables and objective functions [139]. But resource allocation may also be posed as a market equilibrium of demand and supply which is a classical domain of micro-economics [91,136]. When highlighting a decision or control variable or coordination mechanism as "price", in whatever framework, one should ask whether the price reflects human cost perception and economic reasoning to drive decision-making, e.g. to shift HVAC load. Does the market price sufficiently differentiate and qualify the commodities or services traded, i.e. FS? Regarding the control context, can the price stabilize the physical grid states on any time scale, especially when rotational inertia is reduced due to a high i-RES penetration level? These questions are discussed jointly for each methodology tested rather than for each project. As mentioned before, the real-time pricing model adopted in six major field projects plays a dominant role in our review.

5.1. *Micro-economic assumptions*

The crucial market assumption of power being a substitutable flow commodity [91] appears too simplistic to trade flexibility services (FS). The commodities of demand response, i.e. the FS, are not readily substitutable. They are not instantaneous levels of power (or change of power), but power profiles over time that satisfy diverse performance criteria [15] and constraints, such as on response times, ramping slopes, holding time, availability depending on frequency of use, and further criteria such as black-starting capability or impact on reactive power balance. Not even power levels are infinitely divisible; flexible on/off devices have fixed power ratings. Demands on FS result in part from the situations that leave specific patterns of load imbalance to be filled, for instance, substitution or replacement reserves after contingencies. Flexibility offers provided by backup generation plants, batteries, and residential loads are as diverse as the demands put on FS; see e.g. Ela et al. [140] on quality – differentiated service markets for trading FS.

With regard to optimization, a cost-optimal and balanced power allocation over a time period is not obtained by independent myopic or reactive optimizations, i.e. not by market clearings through an algorithm that is like a merit order upgraded to handle the demand side and clocked in five-minute intervals (cf. Fig. 5). Temporal dependence within and among electrical appliances and generators is important; otherwise technically infeasible allocations might result. It is also not obvious why monetary efficiency is emphasized so much as the RTP curves do not necessarily match the true cash flow with test consumers in some experimental setups [118,125]. RTP appears to be used mainly as a means to solve the balancing problem, which could be cast and solved as an optimal (multi-variate, predictive, constrained) control problem that encompasses physical and economic goal variables alike.

5.2. Bid construction and comparison

Market-based TC hinges on the ordering and comparison of all loads and generators on a single price scale. After all, the bid curves should intersect. Loads place their demand bids according to individually perceived need of power, which is determined from end-use constraints[8] and individual preferences between comfort and economy. Diverse types of demand must be prioritized and made comparable before a market can perform the final task of sorting them:

- Is user A's thermal comfort more important than B's (see [91] page 84ff)?
- How do thermal constraints in demand bidding compare to non-thermal goals and constraints to be met, e.g. maintaining the pressure or mass flow rate in a duct, charging a battery to a given level, or meeting a wash program's deadline?
- How do bids for quality-of-service by appliances compare to marginal prices of generators (e.g. gas turbines) which have a well-defined monetary meaning?
- How should a capacity limit approached in a distribution network be monetized?

Obviously, essential weighing (or prioritizing) mechanisms that embody plenty of domain knowledge must be placed between bidding agents and auctioneer to arrange different local needs artificially on a one-dimensional price scale. The simplicity of TC is bought through many adjusting screws and tuning parameters [123,125]. Academic work addressing this knowledge problem [91] remains vague about how to resolve it.

5.3. Are open bidding frameworks safe to use?

Within TC, responsibilities are divided between local distributed agents that construct bids e.g. through their energy management systems and the auctioneering agent that clears the market (cf. Fig. 4). Together they realize core functions of supply security and economy on which the SG system must rely. What is the space of correct tenders permitted? For instance, counterexamples of step functions of bidding (opposed to the more common piecewise-linear ones) are easily constructed such that the intersection yields no (accurate, unambiguous) balancing point, when there are too few producers, consumers, and discrete power levels. How are erroneous or fraudulent bidding strategies detected and hedged against in general? The literature on TC proposes a range of bidding procedures tailored to specific load examples [91,123,136]. However, the authors are not aware of a general guideline (theoretical or best practice) existing to construct valid bidding functions for any common type of household appliance, or a certification procedure that new bidders (HEMS) must go through before entering the market. While such questions can be excluded from academic research, they become urgent at the level of field studies immediately preceding mass deployment.

5.4. From predictive scheduling to real-time dispatch

Contemporary grid operation depends on regulatory frameworks set by ENTSO-E in Europe or FERC in the USA. Unit commitment (UC) as the basic building block plans the allocation of generating units a full day ahead in hourly time steps to meet all future demands and capacity constraints and to minimize operational costs. In this discussion, we generously extend the term UC to also include storage units and flexible demand.

For smart grids hosting high levels of distributed renewable energies (i-RES) the past research decade has seen a surge in predictive resource scheduling and model-predictive control to minimize operating costs; see [139,141] and the discussion in Section 3. These planning tools use detailed weather and demand forecasting, account for stochastic or set-based uncertainties, and are increasingly supported by available software as, e.g., HOMER, WebOPT [142]. The scheduling process is refined several times (day-ahead, intraday,…) as more accurate forecasts become available or uncertainties materialize. The planning horizon is thereby closing in and the time granularity increases.

In the logic of a rolling horizon optimization the real-time dispatch would just play the last schedule in the series, when there is no need or no more time to revise it. TC computes a fundamentally different dispatch through market clearing. Despite the scientific work developed around TC and mentioned before [95,121,136], predictive scheduling and TC in practice seem incompatible and exclusive. Viewing the progress in control theory (MPC, predictive scheduling), pure market dispatch may appear as a dead-end.

5.5. Load control on fast time scales

As mentioned in Section 4.2, with RTP as an energy (€/kWh) tariff the net cost[9] results by integrating the power level (KW) times the price over time. With time-varying RTP, a flexible demand curve can indeed be monetized by the difference w.r.t. some baseline load curve. Still, one may wonder if energy tariffs are universally adequate to trigger or reward demand flexibility. Probably they are with an RTP changing hourly or half-hourly, but at a higher frequency they will eventually be no more [9]. Five-minute clearing intervals are already too short to convey information that people perceive as a tangible cost.

It has been shown that demand-side frequency response can be realized using only local measurements of grid frequency, e.g. [21,134,143,144] and can be implemented decentrally. If a price signal instead had to communicate the desired load changes, price dynamics would have to match the dynamics of the load response elicited [145], which could be a fast, *imminent* response in the form of a *short load pulse*. Accelerating the price dynamics while keeping price amplitudes bounded under an energy tariff would let the effect on the client's electricity bill eventually vanish. Unbounded prices have been proposed to compensate for shorter durations, e.g. inverse sigmoid functions of grid frequency deviation [145]; however, system stability is then endangered depending on communication delays.[10] On fast time scales, therefore, market-based grid control becomes challenging, whether a human or an automated trading agent makes the decisions [9,91].

Still, generation and consumption must be balanced at a seconds time scale, especially when inertia is reduced in the grid. The short-term flexibility offered by HEMS/HVAC systems is increasingly exploited for fast balancing or frequency response [9,21,133,134,146,147]. If the flexibility is an essential service but drawn on irregularly and for short time spans, it cannot be valued by duration (energy tariff) but rewarded through *contractual incentives* [30,148]. Real-time grid control (balancing) and market-based control of supply and demand are thereby separated. For instance, the number of FS provisions per month is rewarded,[11] or rewards are calculated from performance features such as the response time to a request, the accuracy of load following, or the amount of consumption delay. Assuming some load forecast of the same period without flexibility exists, the performance features are extracted from the customers' response

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[8] The urgency of HVAC needs, for instance, depends on the current thermal zone temperature w.r.t. the comfort limits.

[9] Fixed transmission costs or taxes are ignored here.

[10] Averaging the input signal (grid frequency) over *sufficiently long* periods has been proposed in order to regain stability [145] but low-pass filtering also limits the dynamics.

[11] Non-compliance to contractual obligations such as not responding to an emergency DR signal might entail penalties.

profiles. A simpler alternative is to grant customers rebates on their basic energy tariff (e.g. RTP) that depend on the degree of flexibility specified in advance, i.e. on the prior probability or frequency of interventions they would accept [148].

We are unaware of field studies comparable to the OlyPen or the PM City projects where the viability of fast contractually incentivized demand response was tested or proved, such as DR from large TCL aggregations [134]. The projects surveyed in Tables 1–3,5 apparently did not focus on them.

5.6. Smart grid with reduced inertia

Maintaining grid stability under reduced inertia puts higher demands on frequency control and real-time balancing. According to the swing equation [149], the grid frequency (rotational angle velocity) changes inversely proportional to the rotational energy (inertia) existing in the generators and proportionally to the power imbalance. As synchronous generators are being replaced by wind farms and, in particular, by solar PV, rotational inertia not only decreases but disturbances may be detected too late to activate load shedding measures, because the feed-in points are electro-mechanically decoupled from the grid at the DC to AC inverters. Grid instability becomes more likely than in grids with the same physical parameters but with inherent "synchronous" inertia. To counteract this, an equivalent synchronous grid environment can be emulated and fed back through control algorithms implemented in the inverters; several design options exist [150]. Virtual or synthetic inertia does however not replace missing rotational energy that does not already exist in some form and can be harnessed through power electronics and control algorithms, such as the inertia "hidden" in the rotors of wind turbines. Since the amount of rotational inertia varies in grids with large shares of PV and wind power, real-time estimation of inertia is critical [150].

Frequency problems are resolved by removing the power imbalance that caused them, i.e. by activating grid storage or flywheels or fast DR. Teng et al. [151,152] derived the demand of DR balancing power backwards from inertia estimates and the TSO requirements on how to stabilize the grid frequency after an outage or contingency. These specify the largest allowed deviation (nadir), the maximum rate of change of frequency (ROCOF), and the time needed to return to acceptable levels. Synthetic inertia has been tested in real-time simulations and in the field [153] and is available in commercial inverter technology, e.g. for wind power. To the best of our knowledge, the relationship between inertia and HVAC-based demand flexibility, or its impact on inertia, have not been investigated in field projects. Synthetic inertia itself provides a kind of flexibility service for frequency response similar to storage or flexible demand but with rather unique performance criteria. Currently no market for inertia exists but preliminary market arrangements have been simulated [154]. Conventional power or energy tariffs like RTP provide no suitable valuation metrics for trading inherent or synthetic inertia [155].

5.7. Regulatory framework and market structures

TC with RTP/RTT appears to be advocated as a uniform market structure for all organizational layers and especially for interfacing with flexible demand in households [91,136]. It is not clear why such uniformity is advantageous viewing that aggregators [35] are still needed for bundling domestic contributions into marketable flexibility offers. Aggregators form an essential link and a separating interface, selling FS on a flexibility market shared with a utility company (supplier) or BRP or DSO[12] but interacting differently, contractually, with the retail customers that contribute through short-term demand responses. For longer load shifts, on the other hand, the aggregators could pass on the RTP or ToU supplier tariff to the customers. Mixed pricing models like these are being discussed but apparently not field-tested on a large scale. One reason might be persisting doubts that with current market regulation sound business models can be created on top of residential demand flexibility [3,6,156].

The statement found in Kok's Ph.D. thesis [91] on market-based DR control that "the needed coordination mechanism must be fully decentralized and fit into the liberalized energy market" in fact applies to most field projects in Tables 1–3, not only the ones using PowerMatcher/TC: these adopt existing regulatory and market frameworks.[13] Such an experiment design meets the needs of collaborating utility companies who operate in these structures today, and requires less preparatory efforts (possibly including legal exemptions) than a Greenfield study or sandbox game for trying new regulations and value chains, if real legal stakeholders will be part of it.

However, this adherence is also seen as a major barrier to estimate practically realizable flexibility potentials [17], scaled down to the area of field testing. Practical potentials and market conditions interact closely with one another. The scope of a future DR market including aggregator business, the avoidable integration costs at high i-RES penetration levels, the investment and operating costs enabling secure mass participation of TES-based DR could be determined more accurately from field tests. The value of FS should be assessed within this framing, not from the price spans (peak to off-peak) of electricity found in today's wholesale markets (EPEX). Possible savings of flexible consumers are well-defined only compared to inflexible or less flexible consumers in the same test environment, not compared to their current electricity bills.

Present markets reflect a largely centralized generation with a rising share of renewables that still enjoy guaranteed feed-in tariffs (in Germany). Simulations or field tests that accept the present market rules and even draw on volumes and revenue streams from existing markets do not much help answering which kind of FS market (players and roles, transactions, regulation, rules) is needed when 50–80% of generation comes from iRES but more cost-effective grid storages might be available, too.

6. Conclusion

Our analysis suggests that the control and information technology and the economic and regulatory frameworks field-tested and reviewed in the present paper do not yet fully meet the flexibility challenges of smart grids facing very high shares (> 50%) of intermittent renewable generation. Significant benefits have been demonstrated such as effective congestion relief in distribution circuits through flexible domestic demand (including HVAC). However, we see not yet a breakthrough in control technology or market design paving the way to the electricity turnaround state envisaged for 2030 or 2040. Demonstration projects with more real customers are required in which also fundamentally different coordination and market mechanisms should be tested, especially on the fast time scales of flexibility.

Six out of sixteen large field projects rely on the real-time electricity market as the sole coordination and balancing mechanism ("smart grid operating system"); from other projects we do not know this because they focus on different aspects, such as DR potential analysis, measurable benefit for distribution grids by DR, analysis of consumer behavior, development of new IT infrastructure platforms, or test of self-sufficient micro-grid areas.

The basic micro-economic TC/RTP concept was tested first in 2007 in the OlyPen field project and has since been promoted with great

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[12] This could be an ancillary service market (ASM) that maps the diversity, complexity, and quality of flexibility products and unifies the functions of existing balancing markets.

[13] Except for the Chinese Shanghai project [130–132] that ventures the transition from a monopolist supplier market to a more liberalized one.

success and adopted in European projects such as Power Matching City and Couperus. Several limitations and deficiencies are also evident, such as neglecting to differentiate flexibility providers/services by types and qualities in favor of a single flow commodity, as well as ignoring temporal scheduling dependencies. Several FS providing ancillary services, e.g. reactive power or inertia, can not be monetized reasonably on the demand side by simple energy tariffs, which also lose any incentivizing effect on fast time scales, e.g. flexible demand for frequency response. A causal link between pricing mechanism (RTP) and human economic decision-making is not evident in those systems that apply automated bidding agents and market clearing every 5 min. On the other hand, manual DR decisions are slow, partly unpredictable, and suffer from human inadequacies like fatigue or weariness in the long time.

Regarding market-based control, service markets with quality-differentiated FS as products would be a methodical improvement over pure energy tariffs under the flow-commodity paradigm. Uniform quality criteria for specifying flexibility demand and comparing FS from diverse providers (generation, storage, and demand) should be tested in the field.

Methods rooted in advanced control theory are becoming available for reliable and cost-efficient resource allocation, such as stochastic and incremental scheduling and model-predictive distributed control under uncertainties. However, they do not appear to have made it into big field trials so far [81,139]. They could generate the real-time dispatch as a by-product and an end point from a series of increasingly refined schedules. These results should be compared with the market-based dispatch.

With regard to the technological readiness of TES/HVAC operated as mass flexibility providers, we see a few gaps left by the field projects reviewed. One is fast balancing or frequency response realized by aggregated HVAC loads with direct load control (implemented probabilistically and decentralized [18,21,134]), where aggregators provide the compensation. We miss great field trials of this scientifically very active research. Another essential gap is mass integration of residential customers through AMI and DR control devices where field trials focus on cybersecurity and seriously consider alternatives to off-the-shelf 'IoT' components. Regarding new DR-ready HEMS/BAS for the residential markets, the field projects reviewed did not add evidence to us whether TES-based DR creates enough monetary revenues to push the investments.

Many field projects reviewed have taken great efforts to make new FS fit into existing electricity markets and regulation frameworks. Thereby, the experiments do not really help figuring out which new flexibility markets would best support the goals of the energy transition in the long term. Field trials involving real customers and having the freedom to experiment with new regulatory and market conditions could generate market figures endogenously rather than import data from existing markets, and could thereby also shed new light on the revenues of FS achievable in future grids.

Acknowledgements

Grateful acknowledgement is made to BMBF (German Federal Ministry of Education and Research) for providing financial support, promotional reference 13N13297. We further thank Alexander Murray from the Institute for Automation and Applied Informatics (IAI) for careful reading of the manuscript. Finally, we thank the reviewers for their helpful comments.

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