Annex 55

Comfort & Climate Box – towards better integration of heat pumps and storage

Final Report – Part 4

Technical Boundary Conditions in Participating Countries

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Preface

This project was carried out within the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP), which is a Technology Collaboration Programme within the International Energy Agency, IEA.

The IEA
The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a programme of energy technology and R&D collaboration, currently within the framework of nearly 40 Technology Collaboration Programmes.

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)
The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) forms the legal basis for the implementing agreement for a programme of research, development, demonstration, and promotion of heat pumping technologies. Signatories of the TCP are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

Under the TCP, collaborative tasks, or "Annexes", in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex.

The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

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A central role within the HPT TCP is played by the Heat Pump Centre (HPC).

Consistent with the overall objective of the HPT TCP, the HPC seeks to accelerate the implementation of heat pump technologies and thereby optimize the use of energy resources for the benefit of the environment. This is achieved by offering a worldwide information service to support all those who can play a part in the implementation of heat pumping technology including researchers, engineers, manufacturers, installers, equipment users, and energy policy makers in utilities, government offices and other organizations. Activities of the HPC include the production of a Magazine with an additional newsletter 3 times per year, the HPT TCP webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:

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Comfort & Climate Box – towards a better integration of heat pumps and storage

Final report of the combined Annex 34 (ECES) and Annex 55 (HPT)

Part IV – Technical Boundary Conditions in Participating Countries

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Contents

This report presents a comparative overview of the technical boundary conditions for CCBs in the participating countries. As such, it supplements the country reports discussed in Part II of the Annex report series.

1 Strategy and legislation

There is no doubt that there is a policy shift that is considering heat pumps in the decarbonisation of space heating in homes. Examples of the supporting legislation in each participant country is noted below:

Austria: The Government program 2020-2024 states that the combustion of heating oil, coal and fossil gas for heating and cooling must be avoided as far as possible with no new connections by 2025 coupled with district heating supported by geothermal where possible (1) combined with renewable hydrogen in existing gas networks (2) and "Mission 2030" (3) contributing to thermal building renovation, "prosumer work tariffs" and other aspects to ensure that Austria's climate protection targets for 2040 are met.

Canada: There is a strong emphasis on building fabric refurbishment to take the existing build average maximum of 220 kWh/m^2 down to below the current new build of 75 kWh/m^2 (4). Heat pumps are strongly promoted in Ontario and Quebec with other areas working with existing gas networks for gas-driven sorption cycles and/or electric/gas hybrid systems (5). The Pan-Canadian Framework Market Transformation Strategy for the buildings sector has an aspirational goal of a residential natural gas heat pump able to be manufactured and installed cost-effectively (6).

China: The "Plan for Winter Clean Heating in Northern China (2017–2021)" (7), issued by National Development and Reform Commission in 2017, requires 50% of rural residents in Beijing, Tianjin and 14 other provinces in Northern China to substitute electric heating for raw coal by 2019. Challenges include the North-South divide where, as a rule, there is no central heating found in the country south of the Yangtze River. Coal to Electricity is strongly noted in the "14th Five Year Plan and Long-Term targets for 2035" (8) and there is a noted growth in hydrogen.

France: For principal residences, air/water heat pumps with a COP greater than 3.3 were eligible for a tax credit of 15 percent (as of April 2013) and can operate with outside air temperatures of -15°C. The outside unit must be mounted in an open space. Since 2019, the former tax credit system was being phased out and was replaced by a grant system (MaPrimeRénov) for home energy efficiency. A color coded household level of grant is based on occupier income and is paid the end of the works. Technologies include a "solar heat pump" installed by a "registered builder".

Germany: The German Renewable Energy Heating Act pushes all new residential and commercial buildings to include a sustainable heating scheme. From January 1, 2016, construction of new buildings will only be permitted if they use energy generated from renewable sources for space and water heating (9).

Italy: Legislation referred to as "Relaunch Decree" (Decreto rilancio) introduced new tax credits for improvements to Italian properties. These tax credits, called "Superbonus" are intended to cover 110% of the costs of energy efficiency and structural seismic improvements of Italian properties, help with the recovery of the economy and in the process, ensuring tax compliance in the local building industry.

Replacement of heating / air conditioning equipment of residential buildings and boilers (condensation boilers, heat pumps etc.) plus disposal of the old equipment.

The Netherlands: The Dutch government now requires all new buildings to be 'Almost Energy Neutral' (having an Energy Performance Certificate of 0.4) by the end of 2021, and with a target to phase out gas in heating entirely by 2050.

Sweden: In 2017 Sweden adopted a new climate policy framework. The framework consists of a climate act, climate targets and a climate policy council. Sweden's long-term target is to have zero net greenhouse gas emissions by 2045 at the latest (10). Heat pumps are predicted to contribute just under 10% of national heating demand.

Switzerland: With climate change legislation leading to net zero CO_2 emissions by 2050, 90% of new builds already using a heat pump and the expectation that there will be no new fossil fuel boilers by 2030, there is a significant potential for heat pumps (11).

Turkey: The Strategic Energy Efficiency Plan (12) noted a strong need to improve energy efficiency in residential buildings. Excellent solar resources are being exploited but the main heating GHG reduction approach appears to be the change to natural gas (13).

United Kingdom: With the 6th Carbon Budget and the UK White Paper on Energy, the UK intends to install 600,000 heat pumps per year by 2028 (14).

United States: In the United States, the share of heat pump sales for newly constructed buildings exceeds 40% for single-family dwellings (15). Tax incentives based on seasonal performance assist in purchase of new heat pumps.

2 Examples of Housing Stock Energy Use

Housing stock heat loss/heat demand will establish size of heat pump and ergo, electricity demand and heat storage potential i.e., as a demand side management/response participant. This will provide concepts for overall mass production sizes of heat pump based on heating season and assumptions of duration of operation per day (8 hours) and a 20°C temperature difference between inside the building and ambient.

Austria: Single family homes and Terraced Houses typically require <50 kWh/m^2/year for new builds to 380 kWh/m^2/year for existing builds (16). Typical single-family home living areas range from 110 to 175m^2 and duration of heating season is up to 8 months.

Canada: Single family homes require on average 225 kWh/m^2/year (17). Typical single-family home living areas range from 100 to 200m^2 and duration of heating season in Ontario is up to 8 months.

China: Ranges vary depending on the climate zone, but conservative estimates are 14 kWh/m^2/year to 42 kWh/m^2/year (18). Typical single-family home living areas are on average 60m^2 and duration of heating season in Beijing is up to 6 months.

France: RT2020 is the minimum energy efficiency standard for new dwellings calling for 0 kWh/m2/year (19). For residential properties, the standard in the RT2005 is between 150-230 kWh/m^2/year depending on the geographic location of the property, including its altitude. Historically, heat demand has been > 300 kWh/m^2/year. Typical single-family home living areas are on average 120m^2 and duration of heating season in Bourges is up to 7 months.

Germany: Germany's buildings account for about 40% of its final energy consumption and account for 30% of the country's greenhouse gas (GHG) emissions. A substantial share of the building stock was built in the post-war period to an insufficient energy performance level. Energy Performance Certificates (EPCs) are compulsory for all new and existing buildings when sold or rented, and when buildings undergo major energy renovations. The average energy use is 136 kWh/m^2/year (20). Typical single-family home living areas are on average 110m^2 and duration of heating season in Berlin is up to 7 months.

Italy: Detached homes make up 43% of the Italian housing stock. They have heat loss in the range of 105 kWh/m^2/year to 270 kWh/m^2/year (21). Approximately 7 months of a heating season in central Italy heat on average 88m^2 of size of residential space.

The Netherlands: The Central Bureau of Statistics (2020) report that typical heat demand for single family houses ranges from 100-200 kWh/m^2/year depending on size and age. An average heat demand of 13963 kWh/year.

Sweden: Baseline studies noted by Gustafsson (22) noted single family home with a heat loss of 190 kWh/m^2/year. An average house size of 122m^2 is heated for 8 months of the year.

Switzerland: single-family houses (SFH) show a specific final energy demand for space heating ranging between 170 and 200 kWh/m^2/year (23). An average house size of 100m^2 is heated for 8 months of the year.

Turkey: Older stock can be as high 311 kWh/m^2/year with an average is 180 kWh/m^2/year (24). An average house size of 113m^2 is heated for 6 months of the year.

United Kingdom: Most existing homes that have an Energy Performance Certificate (EPC) have a D rating i.e. 101-135 kWh/m^2/year while the Clean Growth Strategy want a C rating by 2035 (60-100 kWh/m^2/year) and new build homes are a B rating (33-65 kWh/m^2/year) (25). An average house size of 118m^2 is heated for 8 months of the year.

United States: With over 80 million single family homes and 11 million heat pumps (26) averaging 200 m^2 of heated space and space heating on average accounting for 42% of residential energy use, newer built family homes are about 121 to 270 kWh/m^2/year. An average house size of 200m^2 is heated for 8 months of the year in its colder zones.

Figure 1 represents the average heat pump heat delivery given assumptions on heating demand derived from national degree days for central locations within each country coupled with 8 hours/day operation and a 20°C temperature difference between inside the building and ambient.

3 Examples of Electricity Flexibility Management and Heat Pumps

This will establish heat pump benefits and the potentials for thermal storage size in respective countries relative to housing size. Power-to-heat, load shifting etc. and economic analysis will be considered.

Austria: Future electric grid congestion is a concern (23). Simulations illustrated that for 250-500 litres of thermal storage (water) was appropriate for 50% heat pump penetration. Greater flexibility (or need of flexibility) is seen with older buildings and renovated buildings rather than new builds and passive houses (27).

Canada: There are examples of power-to-heat examples e.g., Prince Edward Island where there is a concern with additional heat pump integration (28). However, while there are areas with heat pump interests, there is no consideration flexibility management with heat pumps.

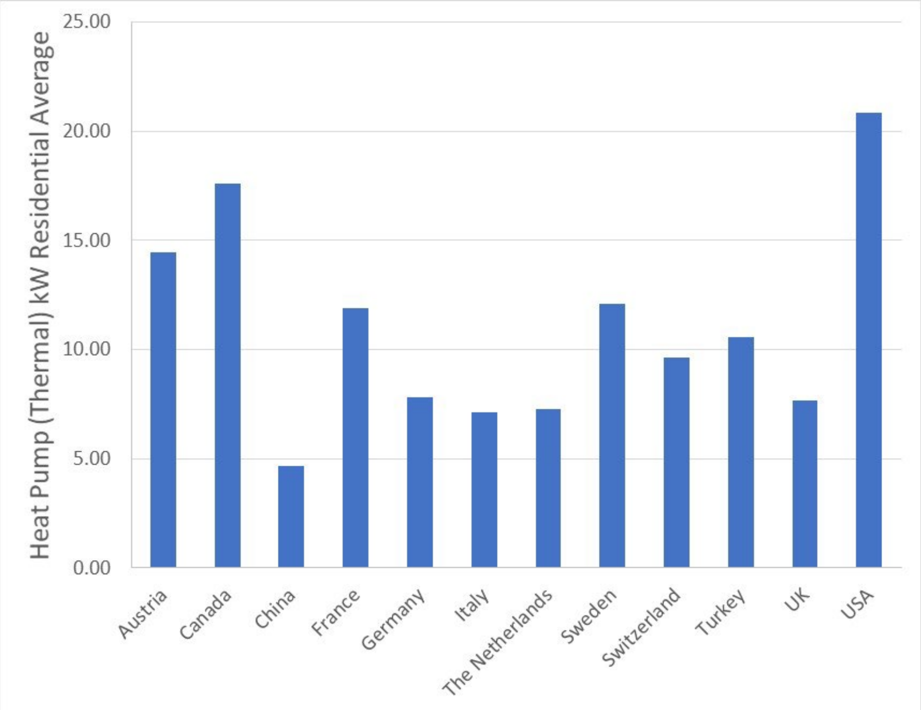

Figure 1 – Approximate heat pump size for single family residential stock of participating nations.

China: The 14th FYP should include targets and measures to support technologies an incentive to unleash the benefits of an efficient power and district heating coupling. The stock of individual heat pumps should be increasing and displace individual coal boilers and stoves (29). Flexibility management is mentioned as a future technology (30).

France: France shows the highest total consumption of electricity for heat pumps in Europe (65.4 TWh per year) (31). Mata el al (32) estimated a flexibility potential of 3.2% for space heating.

Germany: The new ViFlex project is a new project announced in 2020 operating between Germany's largest transmission system operator TenneT and Viessmann and will operate via blockchain, heat pumps with 100% renewable electricity (33).

Italy: There is a strong north-south challenge with greater demand in the north and greater renewable energy supply in the south and electricity congestion challenges create additional problems. Italy's strong heat pump market has not yet stimulated a heat pump demand side flexibility field trial.

The Netherlands: There are numerous examples of flexibility management with heat pumps and thermal storage being deployed in Arnhem for example (34) where 185 litres of water base storage was provided per home in the trial operating with a variable capacity heat pump of 8-12 kW heat output.

Sweden: Air-source heat pumps have been assessed (35) and modelled in buildings (36) with significant use of installed PV capacity via improved self-consumption through a local DC electricity network.

Switzerland: Results from extensive field trials including a 200-home test have revealed that space heating has high potential for flexibility management through heat pumps while hot water is less flexible based on "cut" tests (37).

Turkey: As Turkey is transitioning to higher renewable energy penetration, primarily with solar, it is starting to explore but there are no plans to promote renewables-based heating. However, Turkey is one of the leading countries for solar-water heating which has significant possibilities for heat pump integration.

United Kingdom: Projects include Customer-Led Network Revolution (39), the NEDO Greater Manchester Smart Communities Project (40), the Low Carbon London project (41) and the FREEDOM project (42). Their main findings were that a relatively limited number of mechanisms for the control of heat pump operating times.

United States: An example of electricity flexibility with heat pumps is noted within the PJM market operating in 13 eastern states and over 50 million users. There appears to be no single-family home/residential heat pump flexibility trials despite a well-established market. The need for thermal storage is noted (43).

Therefore, to summarize, electricity network flexibility managed by residential heat pumps and allied thermal storage is not being exploited for reasons of competition from other heating sources, competition from other flexibility management techniques typically at higher network voltages and electricity network transmission level, and a lack of policies, regulation, controls, aggregation, and end-user acceptance.

4 Considerations for (Air-Source) Heat Pump Design

The heat pump in question is that suitable for single family homes. It has been established that such units will deliver on average 5 to 20 kW of heat. The best heat pump performance is achieved at the lowest heating system temperatures. Table 1 summarizes the minimum temperature of typical heat wet distribution systems with the housing stock of each participant state. Given the expected downward trend in single family home heat distribution temperatures, the temperatures selected for such system are 60°C and 40°C for the design concept. The is now a discussion on the choice of refrigerant and components for a 10kW heat pump.

Regarding refrigerants, low global warming potential (GWP) is an important factor. EU F-gas regulations will reduce the current dominant hydrofluorocarbons (HFCs) placed on the market to 21% of current levels by 2030. R410a is very prevalent in the residential heat pump market and its direct replacement is challenging. An example of further constraints is from the U.S. Environmental Protection Agency where its Significant New Alternatives Policy Program (SNAP) prohibits the use of high-GWP refrigerants in newly manufactured domestic refrigerators and freezers, including R410A. Sires et al (44) proposed reduced GWP R452B and R454B with R454B show marginally superior coefficients of performance (COP) while R32 is becoming popular. Yu et al (45) screened a number of R410A replacements for lower GWP (<150) and generated mixtures of refrigerants, all of which have mild flammability. Theoretically, all COPs were reduced by 4% to 14% so drop in alternatives with low GWP may not be feasible. Natural working fluids e.g., R290 (propane) have similar performance in purpose designed systems (46) and there are a number of significant manufacturers. R744 (CO_2) is growing in popularity for water heating/air heating systems via a trans critical cycle but with only a small number of residential scale manufacturers.

Considering the main mechanical components of the heat pump, system noise must be taken into account. In terms of sound legislation, the key legislation comes from the UK BS4142 for example and the World Health Organization. Regarding BS4142, 35 dB(A) to 40 dB(A) at night is "typical" suburban noise level. There is also a need to add 5 dB(A) for a "tonal" quality of fan and if the sound source is 10 dB(A) above background noise "complaints may be expected". IEA Heat Pumping Technologies Annex 51 "Acoustic Signatures of Heat Pumps" sees over 60dB(A) for operation and defrost activities (47). Therefore, selection of acoustic covers, fan types and operating speeds, compressor speeds, pipe sizing (velocity) etc. must be consider. However, variable speed drives (compressors, fans, pumps) are necessary components in energy efficiency and in demand side response roles (when accompanied by household heat distribution controls). The concept is simple in that the thermal inertia of the building can provide a portion of demand side response (through a heat pump "off" or "throttling" phase) with throttling of the heat pump leading to 40% to 65% load reduction depending on the building and outside air temperature (48).

Therefore, what would be an ideal air-source heat pump of approximately 10kW heat capacity. Typical variable speed drive scroll compressors offer speeds from 20Hz to 120Hz but with a performance penalty (49) for different air-on temperatures (°C). Weather compensated control (temperature of heat appropriate to maintain thermal comfort for a given ambient temperature) can also offer a degree of flexibility and demand reduction by reducing the heat distribution temperature based on building response time. Links with building heat distribution controls to reduce temperature in unoccupied spaces can also play a role in reducing demand at periods of high electrical demand.

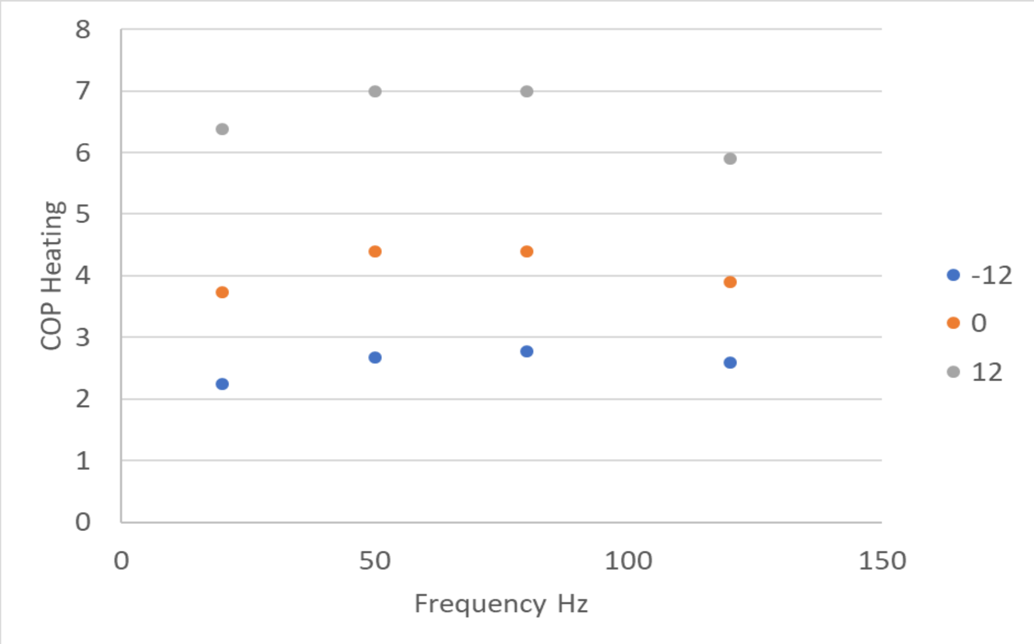

Figure 2 – Heat pump variable speed performance penalty example.

Low GWP/natural fluids will need to be utilized in residential air source heat pumps in the near future. Regardless of the choice of fluid, in changing from R410a, it appears that a low GWP working fluid will be challenging to find. R466A (R32, R125 CF3I, or trifluoro iodomethane) with a GWP of 733 appears one of the most promising in terms of performance with a 5% increase in performance (50). Therefore, specialist fluids (R744) requiring a significant system design shift or lower density refrigerants must be utilized e.g. R290 (flammability), R444B (mildly flammable, GWP = 295) or R455A (mildly flammable, GWP = 146). As previously stated, R290 is well known but the relative performances of the other lower GWP alternatives are less so. R444B shows a 4-5% increase in performance over R407C (51). R455A will have a lower performance that R410A. So R290 may become the fluid of choice alongside a limited number of milder flammability low GWP mixtures as current refrigerant chemistry has been largely explored.

5 Thermal Storage Optimisation

Thermal storage sizing will be dependent on several factors including integration of household variable non-dispatchable renewable energy (e.g. solar), weather/climate, integration of local electricity network variable non-dispatchable renewable energy (e.g. wind), the impacts of a weak electricity network in terms of the electrification of space heating and the electrification of transport. In addition, for thermal storage, there are challenges of compactness in retrofitting air-source heat pumps and thermal stores in existing single-family homes and potential acceptance of aggregation control of operations in terms of electricity network capacity management.

Regarding building integrated renewable energy e.g., solar, the challenges are to potentially increase self-consumption in terms of electricity (Photovoltaics) for personal economic purposes and/or limiting export to the local electricity network. The latter has ramifications for local electricity network capacity and for electricity voltage transformer sub-station abilities to reverse flow. Heinz and Rieberer (53) simulated a retrofitted single-family home in Zurich, Switzerland with PV, an air-source heat pump, and thermal storage options (water) ranging from 500 litres to 2000 litres. The proposed retrofit reduced the heating demand by 27% and concluded that "existing" radiators where a better mechanism for addressing PV integration. Thus, 5 kWp PV and a 1 m^3 thermal energy store was the most economic for a 185m^2 single family home. Solar thermal was addressed by Pinamonti and Baggio (54) who modelled three single family homes of low, medium and high insulation approaches in northern Italy. A reference case of an air source heat pump and domestic hot water (DHW) store linked to an underfloor heating system was added to systematically with buffer storage, solar thermal and finally PV and a battery. The DHW and the buffer storage were typically 150 litres each and are served by up to 10m^2 of solar thermal/PVT panels. Insulation is important and its inclusion reduced the needs for buffer storage while battery inclusion serves the role of local building self-consumption of PV generated electricity. Prosumer approaches matching supply with demand can challenge self-consumption strategies (55) due to their lower capital cost approaches.

Local distribution electricity networks have variable, non-dispatchable electricity generation e.g. wind and solar. This then becomes the integration of so-called "smart grids" and "smart buildings" where smart grids and smart buildings utilize or conserve electricity to "balance" the local electricity network. Challenges typically arise around voltage and frequency of electricity, curtailment and reactive power control depending on supply and demand activities. Aggregation of heat pumps and thermal storage can then operate within "arbitrage" i.e., storing heat via heat pump operation at times of excess renewable electricity or using heat from the thermal store at times of high electricity demand. Shah et al (56) successfully operated a higher temperature cascade air-source heat pump and 600L of water based thermal storage responding to wind availability in a detached family home without fabric retrofit and utilizing the existing hot water radiator system originally designed for a gas boiler with flow and return temperatures of 80°C and 60°C respectively.

Therefore, the future challenge is potentially to move beyond water as a storage medium. This would be based on materials that have a superior thermal storage density e.g., phase change materials (PCMs) to facilitate compactness in the retrofitting of an air-source heat pump with thermal storage. Osterman and Strtih (57) reviewed vapor compression heat pumps and thermal energy storage and concluded that an important aspect of PCMs is space savings (compared to water) and optimization is required in design and control. Considering only diurnal thermal energy storage, what are the factors that influence design and what may be their ranked order?

When considering the electrification of heating, actions that mitigate negative impacts on the electricity network must be prioritized. Therefore, reduction of thermal demand (e.g., building insulation) will reduce air-source heat pump electricity demand and it has been shown that it also reduces thermal storage size (54).

The electrification of heating in areas of weak electricity network will need to consider diversity factors, aggregation and potentially their role electricity network ancillary services (58). However, demand forecasting and status of individual heat pump and thermal energy storage systems to meet that demand is not well established, as are the relevant communications and demonstration of revenues e.g., against infrastructural upgrade deferral for example.

Nevertheless, the challenge for traditional PCMs e.g., paraffin waxes, is their relatively constant temperature with changing phase. Such a store may be considered as reducing heat pump flexibility strategies e.g., weather compensation. However, it should be remembered that typically, the thermal energy store will be charged by a heat pump operating with off-peak/local excess electricity. Therefore, provided that the PCM (and the current typical requirement of 10K temperature difference for heat transfer) is of a type and is heated to a temperature sufficient to operate the space heating of the building and subject to any electricity network and heat pump constraints, this should be less of an issue.

And finally, we must consider the electricity distribution network. Furusawa et al (59) noted the constrained connections for distributed generation in European countries. Sterchele et al (60) noted the need for greater numbers of flexible power plants for increased numbers of heat pumps in Germany, with up to 50% of the weekly load being associated with heat pumps in the inter periods. However, the challenge for single family home air-source heat pumps is the visibility of the electricity network below certain substation capacities (61).

6 CCB and Smart Grid Readiness

In addition to the methods proposed in the report # 6 to rate the energy flexibility of the CCB, the definition of the smart grid readiness of the CCB is relevant. The same approach as proposed for smart grid readiness (SRI) in report # 6 is adopted. Therefore, the smart readiness is quantified on the basis of the functionalities that each service related to the CCB can provide: the list and quality of functionalities included in the CCB can be used to provide the score.
Following the SRI approach, an evaluation matrix can be defined, where the domains and services of the CCB are identified (Figure 12):

1. **Domain**:
    a. Heating
    b. Space cooling
    c. Domestic Hot Water (DHW) production/storage
2. **Services**:
    a. Energy savings on site
    b. (Predicitve) maintenance, fault prediction
    c. Comfort
    d. Convenience
    e. Information to occupants
    f. Grid flexibility and storage

In this context the focus is on the energy flexibility of the CCB in relationship with the services provided to the grid and/or to the possibility of increasing the renewable energy sources (RES) self-consumption on site (storage capacity), i.e. "Grid flexibility and storage".
Each Service is rated on the basis of its **functionalities**.
Possible functionalities identified for the **Service "Grid flexibility and storage"** are:

1. Communication type: type of Protocol (evaluated on Openness, Interoperability, Maturity, Supported functions….). It has an impact on type of information exchanged, actions allowed and possibility of activation of a communication with external or internal parties.

- The communication can indeed be with an energy manager that could be in-home or in the cloud (e.g. managed by an aggregator). More details on available protocols can be find in [21].

2. Functions:
    - Limit consumption
    - Shift consumption
    - Power modulation
    - Pause a task
    - Buffer energy
    - Switch energy type
3. Type of control: rule based, predictive or model predictive control. The type of control determines the complexity of strategies that can be implemented and thus the flexibility that the CCB can provide.

7 Concluding Comments

In optimizing an (air-source) heat pump and allied thermal energy storage heating systems for single family homes, it is obvious that it is very location dependent. Heating demand is based on building size, solar orientation and envelope quality, weather and climate and lifestyle choice. The home can take advantage of local renewable energy (whether building integrated or delivering the local low voltage electricity networks) and any constraints on increased electricity consumption imposed by the local electricity distribution network. Heat pump operations are improved by lower temperature heat delivery systems (e.g. underfloor heating) in terms of performance, but considerations must be made for potentially longer running times, thus reducing thermal energy storage opportunities during colder periods. Superior building envelopes reduce the size of thermal energy storage requirements but then electricity network constraints, electricity network ancillary services and aggregation may influence thermals storage sizing.

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