Heat Pumps and Thermal Storage: Canadian Perspectives

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Heat pump and thermal storage systems can support an increased adoption of heat pumps by providing a more flexible link between the building and electrical grid. This article explores the development of these systems from a Canadian perspective, outlining key design requirements, presenting potential system solutions, and examining demand reduction potential through initial simulations. Findings provide an important basis for ongoing research to better adapt these systems to the Canadian climate and market.

As the world transitions towards a decarbonized economy and infrastructure, efficient renewable energy technologies are of great importance. Canada's Market Transformation Roadmap [1] presents a framework for the increased adoption of these systems, outlining aspirational goals regarding system performance (seasonal heating efficiency >100%) and the integration of renewable energy. Heat pumps respond well to these objectives, but their widespread adoption can be challenging for electrical utilities.

Despite their energy savings potential, heat pump use coincident with other electrical end uses can increase house-level electrical demand. This increased demand can be particularly problematic for utilities when it occurs with a high degree of simultaneity (i.e., for many homes in a given region at the same time). Air-source heat pumps are a popular choice of heat pump integration in Canada, but can be especially problematic in this context. These systems tend to experience capacity degradations at colder outdoor temperatures, necessitating the use of supplemental electrical resistance heating. Given the link to outdoor temperatures, this tends to occur with a high degree of simultaneity across a given region [2], creating larger aggregated loads. This added electrical demand can challenge the generating capacity of the grid, imposing practical limits on heat pump adoption. Furthermore, in regions where electrically based heating is already common, it also presents a challenging business case for utilities, as heat pumps may reduce overall electricity use but still account for large peak demands.

Despite these challenges, heat pumps can also be an important tool in supporting more energy-flexible electricity grids. Integrating heat pumps with thermal storage can provide a flexible link between the thermal and electrical networks of the building, allowing the heat pump to adapt its operations to the needs of the grid without sacrificing thermal comfort. This article explores Natural Resources Canada's ongoing research on air-source heat pump and thermal storage systems, providing Canadian perspectives on design requirements and system solutions in line with contributions to IEA HPT Annex 55.

System Design: Requirements and Design Objectives

Annex 55 outlines nine key quality criteria to structure the discussion on heat pump and storage systems. While criteria such as affordability and customer appreciation are clearly important, from a technical perspective, Canadian work has focussed on addressing three criteria:

Suitability: An emphasis on air-based distribution (common in Canadian homes), supplying both heating and cooling (growing demand for cooling), and maintaining strong cold climate performance (to reduce electrical peaks associated with activation of electric resistance auxiliaries).

Integral Design: A focus on an integrated set of physical components and controls, in a similar manner to current generation heat pump systems. This supports ease of installation and commissioning, and better ensures consistent performance.

Compactness: An emphasis on minimizing storage size, as Canadian homeowners and builders typically place a high value on maximizing livable area, at the expense of added space for mechanical systems. Prioritizing compactness is particularly important for the retrofit market, where system installation must be designed around existing constraints.

Exploring Storage Options: Thermal Storage for Canadian Homes

Selecting a target for the energy storage capacity of the system is a critical design decision, influencing size, cost and load shifting potential. In this study, sizing is based on covering the maximum thermal demands of the building for a 2H peak event occurring during either morning (6 AM – 9 AM) or evening (4 PM – 8 PM) hours. For a typical new construction home in Montreal, this equates to a required storage capacity of 15 kWh. However, given variations in climate and housing size/construction, a flexible approach is likely required in Canada to adapt capacity to the context of the actual installation.

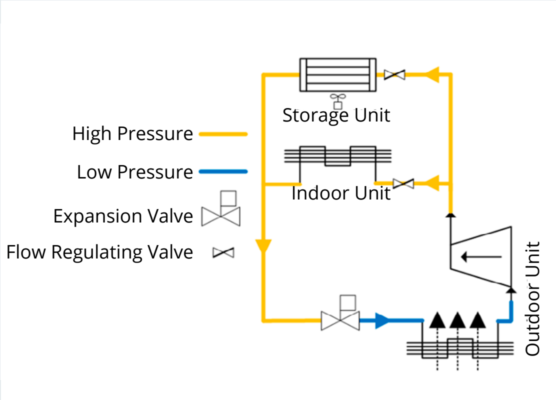

Figure 1: Diagram of a Heat Pump and Storage Concept

Material selection also has an impact on the physical size of the thermal storage. Given the emphasis on compactness, phase change materials (PCMs) are of particular interest in the Canadian context. An initial analysis shows that, by using commercially available PCMs with phase change temperatures of 40-45°C, storage volumes can be reduced by as much as 60% (vs. water-based storage, temperature rise 15°C). These reductions show the potential benefits of using PCMs, although final material selection must consider additional factors, including thermal conductivity, chemical stability, and relative price.

Integrating Heat Pump and Thermal Storage: A Cycle-Level Analysis

The way in which thermal storage is integrated with the heat pump has important implications for the performance, energy flexibility potential, and suitability of the system. For the Canadian systems examined in Annex 55, the heat pump and storage system consists of three main components: an outdoor unit (Refrigerant - Outdoor Air HX and Compressor), indoor unit (Refrigerant - Indoor Air HX), and thermal storage unit (Refrigerant - PCM heat exchanger and fan). Despite the relative simplicity of this component list, system performance is closely tied to the way in which these components are configured.

Figure 1 shows one configuration examined under Canada's contribution to Annex 55, suitable for both ducted and ductless air-to-air heat pumps. The concept uses excess thermal energy stored during off-peak hours to directly heat the building, avoiding heat pump compressor use during peak periods. Energy is added to the storage unit (i.e., charged) by using the storage as an additional condenser. During off-peak hours, a portion of refrigerant exiting the compressor passes to the storage unit. Here, the refrigerant passes through a series of pipes surrounded by a storage material, allowing a direct refrigerant-storage heat exchange without the need for secondary heat transfer fluids.

During peak periods, energy may be removed from the storage unit (i.e., discharged) by passing room air over the surface of the storage via a fan. This provides a degree of space heating, without the need to operate the heat pump compressor.

One major challenge in designing heat pump and storage systems is ensuring sufficient charging times. Heat pump and storage systems may be required to respond to multiple peak periods during the same day (e.g., morning and evening events), necessitating sufficiently fast charging during off-peak hours. These charging times are closely related to the amount of heat pump capacity dedicated to charging (i.e., whether the storage can be charged using the full, or partial, capacity of the heat pump).

Figure 2 examines the impact of part load on idealized charging times, tabulated using a simple heat pump cycle model of a two-ton air-source heat pump. Results clearly show that, in order to sufficiently charge between morning and evening peak periods, systems would need to charge above 70%-part load.

Enhancing the Energy Flexibility of Canadian Homes: A Building-level Analysis

A simulation-based approach is used to illustrate the performance of these systems in a newly constructed single-family home in Montreal, Canada. The studied heat pump and storage system follows the configuration outlined in Figure 1, and is operated to avoid compressor operation during peak periods. During these times, the storage unit is used to directly heat room air. Charging occurs during off-peak hours, when the heat pump is operating below its maximum capacity.

Figure 3 compares the electrical demand during peak hours for three space-heating systems: Electric baseboards (Elec. BB), a variable capacity heat pump without storage (VCHP), and a variable capacity heat pump with storage (VCHP + Storage). While the VCHP (without storage) greatly reduces electrical demand for 99% of operating hours vs. electric baseboards, maximum demand for the two systems is similar. During the coldest winter periods, outdoor temperatures fall below the minimum operating temperature for the selected heat pump (TOutdoor <-25°C). The VCHP is therefore unavailable to operate and auxiliary resistance elements must be used to provide space heating, increasing demand. This operation clearly poses a challenging business case for grid operators, who may sell less electricity but still be required to maintain infrastructure for the worst-case peak. On the other hand, the VCHP + Storage case appears to offer meaningful demand reductions vs. both systems throughout the operational window, primarily because auxiliary resistance heating can be offset through the storage.

It is important to note that these results are highly specific to the case examined. The ability of the system to displace electrical demand is closely tied to whether the heat pump is able to charge the storage during off-peak hours. Should the building thermal load remain high during these periods, the system may have limited ability to charge, reducing the magnitude of demand reductions obtained. This impact may potentially be mitigated

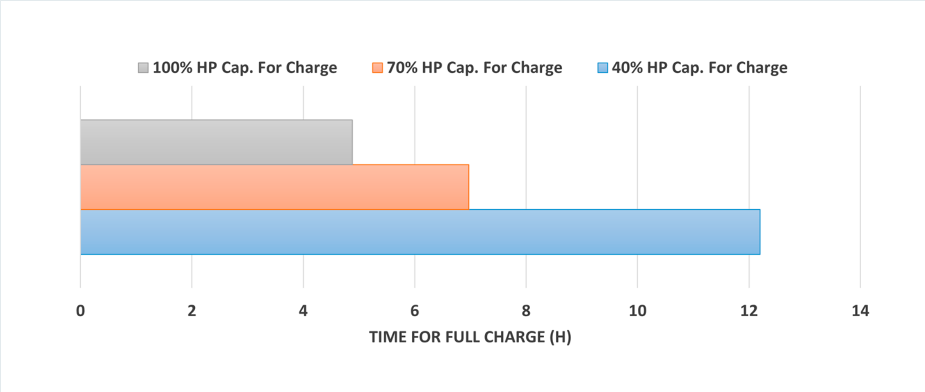

Figure 2: Impact of Part Load on Charge Times

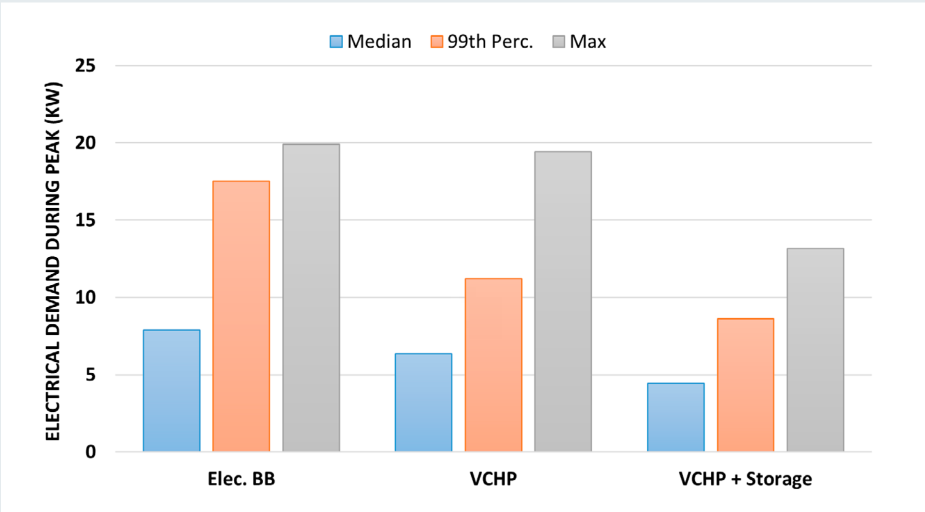

Figure 3: Impact of heat pump and storage on electrical demand in a single-family Canadian home

by selecting a larger capacity heat pump, or by taking advantage of the additional thermal storage inherent in the building mass. Regardless, it is clear that system sizing and integration is a critical issue that must be addressed to capitalize on the potential of these systems.

Conclusions and Future Work

Heat pump and thermal storage systems can improve the interaction between the building and electrical network by allowing heat pumps to adapt their operations according to grid needs without sacrificing thermal comfort. This ability positions heat pumps as a key tool to support future smart grids, thus facilitating a more widespread adoption of heat pumps and renewable energy systems. However, these systems must be well adapted to their target market. This article has examined the development of air-source heat pump and storage systems from a Canadian perspective, tracing how design requirements impact system solutions, and examining potential demand reductions in Canadian residential buildings. This article presents initial results from an ongoing project exploring heat pump and thermal storage systems in Canada. Recent work has focussed on enhanced modeling to better assess energy transfer rates to/from the storage, and support the examination of additional system configurations. Simulation work will also be expanded to further assess performance in other buildings and regions in Canada. Experimental activities are also planned to provide a practical understanding of performance in the Canadian climate.

References

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