

On the Necessity to Integrate Power Flexibility in Cooling Systems

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Abstract. Today, cooling systems are widely used, notably with the unprecedented growth of data centres and building space cooling. These thermodynamic systems are powered mainly with electricity, and their peak loads are generally associated with very high carbon footprints. At the same time, congestion of the grid due to high load or renewable power injection is becoming an issue for all actors involved with electricity (producers, providers, consumers, and prosumers). Actually, both the price and associated carbon footprint of electricity usually fluctuates along with the charge of the network. This paper discusses the integration of power flexibility (PF) in new and existing cooling systems to avoid a possible cold crunch in the near future. After defining PF, several cooling systems archetypes are presented. Three possible ways to integrate PF are explained: flexibility by thermal inertia and energy storage (thermal and electrochemical). While PF principally targets the reduction of stress on the electric grid, other benefits can also be achieved, e.g. mitigation of direct carbon emissions and decrease of costs related to operating the refrigeration system. We explain how better management of energy transits and possible imbalance in electricity networks can be achieved by thermal inertia. The choice of integrating thermal storage or electric battery is discussed, and both solutions are considered in a specific case study. The study aims at better management of power loads on electricity network caused by the cooling system and could be useful for anyone involved with grid management and/or refrigeration systems.

1. Introduction

Human production of cold has been a challenge, and today, modern society means, among other things, refrigeration at every corner. In 2015, 17% of the electricity used worldwide was devoted to refrigeration, providing employment for nearly 12 million people [1] in a wide range of activity sectors (see Figure 1). Refrigeration has a direct impact on human health through the preservation of foods, pharmaceuticals and medicines, and with magnetic resonance imaging and low-temperature treatments (cryosurgery or cryotherapy). In the industry, refrigeration is necessary for numerous manufacturing and conservation processes and is found in food and drink industries, chemistry, plastic processing, and mechanical engineering. In the building sector, air conditioning plays a key role in the economic and social development of warmer countries. One important factor in the booming demand for refrigeration



is global warming. Projection of the evolution of cooling degree days that measure the impact of the weather on the overall need for cooling shows an increase of around 25% globally by 2050, with the most significant increases occurring in already hot places where income and population are rising fastest. Although refrigeration is becoming affordable for more people, access to cooling is still uneven over the world and is a major social issue; 90% of the people from the US and Japan have air conditioning (AC), against 8% of the 2.8 billion people living in the hottest regions of the world [2]. Most of the energy used for cooling is in the form of electricity. For example, in the United States in 2005 for the AC sector, 99.9% of all units shipped were based on electricity-driven technology [3].

From the electric grid, this expansion is less appealing and could soon become critical. This possible upcoming phenomenon is called a cold crunch. Even if the penetration of renewables (RE) has never been as intense, the mismatch between the erratic production of solar and wind-based electricity and requires the necessity to anticipate load problem on the electric infrastructure. Peak demand of grid electricity is usually covered by fuel-based power plants, inducing a very high carbon footprint (at a world average Global Warming Potential (GWP) of circa 0.5 kgCO_{2-eq}/kWh [2]). As a result, refrigeration is responsible for a massive amount of greenhouse gas (GHG) emission (see Figure 2) due to direct emissions (leakage) of refrigerant and indirect emissions originating from electricity generation.

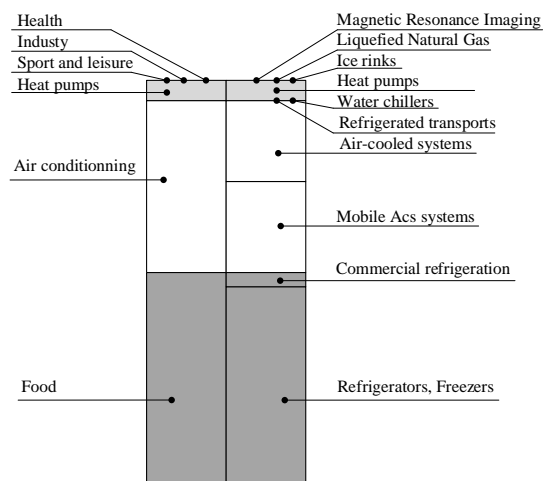


Figure 1. Share of cooling systems (total of 3.06E9 units) by sectors of use and by system types, based from data published in [1]

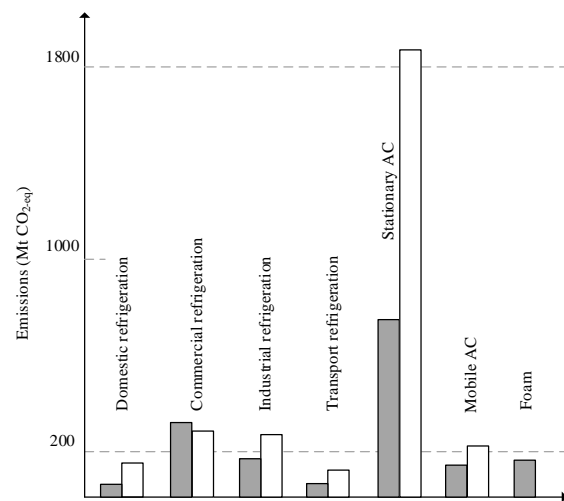


Figure 2. GHG emissions associated to refrigeration [4]. Dark grey: direct emissions. Light grey: indirect emissions.

To limit the impact of an unprecedented expansion of cooling demand on the electricity network infrastructure, different measures are proposed. One consists of increasing the energy efficiency of cooling systems through enforcement of standard and labels, combined with a reduction of cooling needs with tighter building codes. Another is the massive implementation of RE generation. However, even the combination of both will not be sufficient to prevent the installation of more energy and power for electricity generation [2]. In this paper, we explore the possibility to integrate power flexibility (PF) in cooling systems. After a semantic definition of PF, the benefits that can be obtainable by PF are reviewed (Section 2). Section 3 reviews the most frequent cooling systems for understanding how PF can be practically implemented in new and existing systems (Section 4). Practical implementations of PF are addressed in Section 5.

2. What is Power Flexibility (PF)?

Flexibility in the power system, called power flexibility, can be defined as “the modification of generation injection and/or consumption patterns, on an individual or aggregated level, often in reaction

to an external signal, in order to provide a service within the energy system or maintain stable grid operation” [5]. In our context, the electrical consumption for cooling is shifted over time to serve multiple goals: increase of the self-consumption rate either locally or in a local microgrid, congestion avoidance on the local distribution grid, GHG mitigation by an optimum use of low-carbon energy sources, participation to different energy and power markets. The main objective of PF is to temporally disconnect the electrical energy demand usually linked with the instantaneous cooling demand. The means by which the temporal disconnection is performed lies in the deployment of technical artefacts and regulation strategies (see Section 4).

3. Cooling systems archetypes

The majority of deployed cooling systems in use throughout the world are based on vapor compression cycle technology. The process uses refrigerants, often human-made gases with significant GWP, releasing or absorbing heat respectively during condensation and evaporation. Food storage, by using, refrigerators, freezers and cold storage rooms, with AC in residential and commercial buildings, represents 95 % of cooling systems units (see Figure 1). For these two sectors, compressor-based refrigeration equipment dominates the market due to its low initial cost, low operating cost by superior efficiency, and good safety record. Replacing electricity used to drive mechanical compressors by heat is possible through absorption technology. However, its use represents a share of just over 1% of natural gas against a total electricity use of 2000 TWh in 2016 for cooling purposes [1]. Other sources of heat, such as excess industrial heat or solar thermal energy are potentially promising technologies. Today, absorption systems are large ACs, typically used in the non-residential sector. A less common and simpler form of cooling is evaporative cooling, which is also used for AC. Other emerging technologies (e.g. desiccant cooling, thermo-acoustic, magnetic cooling) has developed much slower than predicted [3]. The most current technologies found in the market for food storage and space cooling are:

3.1. Packaged systems

These refrigeration appliances are unitary systems, containing both the condenser and evaporator in a single box. The customer buys a ready to install system (e.g. refrigerators, freezers, and ACs). At the domestic level, ACs often consist of window units that fit into standard window frames. Common in hotels, packaged terminal ACs consist of the evaporative unit on the inside, generally under a window, with a grilled opening passing through the wall, connected to the condensing unit on the outside. Packaged portable units are designed to be easily transported from room to room inside a building, with a mobile duct to evacuate the hot air from the unit to the exterior. Packaged rooftop units are larger packaged chiller systems delivering cooled air into the building through ducts.

3.2. Splits systems

Ranging from small room units to very large systems (large building complexes), split systems have an evaporator placed inside the space to cool, which is connected through piping that carries the refrigerant to the evaporator, or air handling unit, to the condenser located outside. Split systems – either individual mini-split or multi-split ACs – represent the vast majority of ACs in use today.

3.3. Chillers

Almost exclusively in commercial buildings, large residential blocks and district cooling networks, chillers are large central systems ACs that produce chilled water and distribute it throughout a building or cooling network through pipes to an indoor system that cools the air. Compression (centrifugal, reciprocating or screw driven) cycle chillers are electric powered and water or air cooled (35 million units, representing 60% of total commercial air-conditioning needs), and thermally driven chillers (absorption) account for another 5.5 million units [2].

4. How to integrate PF in cooling systems

In this paper, three possible ways to integrate PF in cooling systems are investigated. They consist of thermal inertia, electrochemical batteries, and thermal storages. An overview of the different possible inclusions of these elements enabling PF is presented in Figure 3.

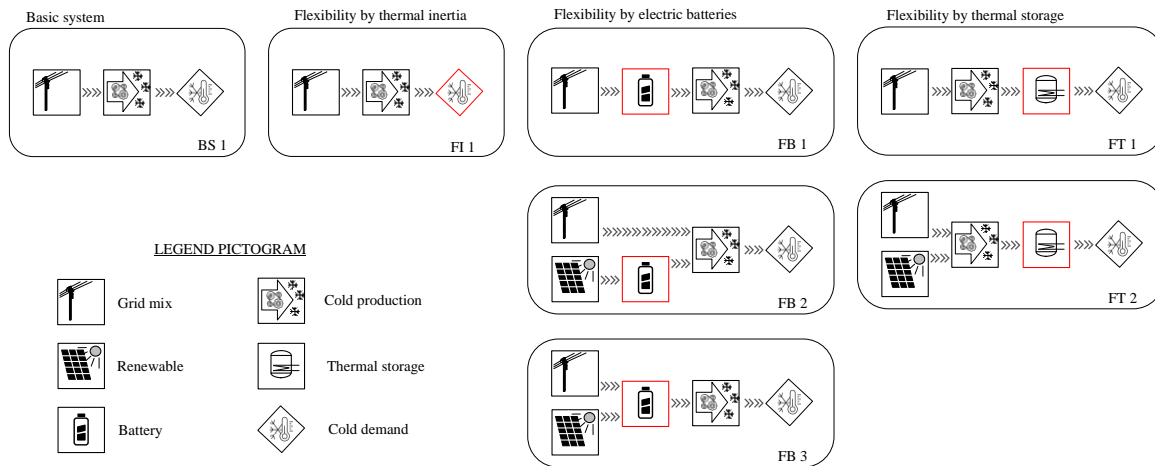


Figure 3. Example of PF integration in cooling systems.

4.1. Flexibility provided by the thermal inertia of the refrigerated mass

Using the refrigerated mass as thermal storage is an a priori interesting option, as it requires no dedicated storage appliance. Let us assume that a refrigerated mass with a heat capacity C is stored in an envelope with heat transfer coefficient K . The mass temperature set point is T_m (ref) and the outdoor temperature is T_o (assumed constant for simplicity). Then, the thermal power P_{th} required to maintain the mass temperature constant is given by:

$$P_{th} = K (T_o - T_{m\ ref}) \quad (1)$$

Assuming efficiency η for cold generation, the corresponding electrical power P_{el} can be calculated:

$$P_{el} = \eta \cdot P_{th} = \eta \cdot K (T_o - T_{m\ ref}) \quad (2)$$

If the refrigerated mass temperature T_m may vary in the range $T_{m\ ref} \pm \Delta T$, the thermal energy E_{th} that can be stored in the mass is given by:

$$|E_{th}| \leq E_{th\ max} = C \cdot \Delta T \quad (3)$$

The corresponding electrical energy E_{el} is given by:

$$|E_{el}| \leq E_{el\ max} = \eta \cdot E_{th\ max} = \eta \cdot C \cdot \Delta T \quad (4)$$

Assuming an initial temperature equal to $T_{m\ ref}$, electrical power can be cut for a maximum duration $t_{off\ max}$ equal to:

$$t_{off\ max} = \frac{E_{el\ max}}{P_{el}} = \frac{C}{K} \cdot \frac{\Delta T_{max}}{T_o - T_{m\ ref}} \quad (5)$$

where ΔT_{max} is the maximum permitted temperature deviation for the refrigerated mass. Starting from the same initial state, electrical power can be increased up to the peak available power $P_{el\ max}$ for a duration shorter than or equal to $t_{on\ max}$:

$$t_{on\ max} = \frac{E_{el\ max}}{P_{el\ max} - P_{el}} \quad (6)$$

Hence, the refrigerated thermal mass can be modeled as an ideal battery (see Figure 4).

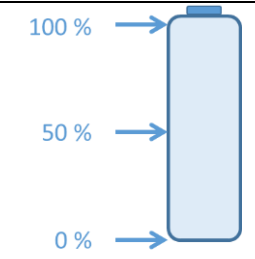


Refrigerated mass temperature	Energy in “battery” (50% SoC: 0 Wh)	Battery model	May. charge and discharge power
$T_{m\ ref} + \Delta T_{max}$	$E_{el\ max} = \eta \cdot C \cdot \Delta T_{max}$		 <i>Discharging power</i> $< P_{el}$
$T_{m\ ref}$	0		
$T_{m\ ref} - \Delta T$	$-E_{el\ max} = -\eta \cdot C \cdot \Delta T$		 <i>Charging power</i> $< P_{el\ max} - P_{el}$

Figure 4. Refrigerated mass modeled as an ideal battery system.

However, real systems do not behave as described above for the following reasons:

1. Most cooling systems are not variable loads: they work in on – off mode (i.e. P_{el} is either 0 or $P_{el\ max}$), and they are regulated by a hysteresis controller.
2. Inlets of warm mass and outlets of cold mass may fundamentally change the behaviour.

Unlike other types of storage, storage in the refrigerated mass cannot be considered as reliable, and its control must account for that fact.

4.2. Flexibility given by electrochemical batteries

When integrating flexibility by an electricity storage, the battery is placed up front the refrigeration machine. Technically, it involves an electrician, and in practice it can be easily implemented in the existing standard environments. The storage capacity could range from small to medium size (domestic), but due to its high cost, the autonomy criteria alone cannot, most of the time, justify the lack of economic viability for a large capacity. As of today, Lithium-ion (Li-ion) is the benchmark technology due to its energy density, in and out power and conversion efficiency. Progresses is constant in the field of electrochemistry, and examples of current achievable characteristics of Li-Ion batteries are presented in Table 1. One important feature of batteries is the decay of the storage capacity over their use. The end-of-life of a battery is usually determined when the storage capacity reaches 80% of its initial value, but there is nothing against using them longer, especially because of their relatively high environmental impacts (Table 1).

A battery is generally not implemented alone (case FB 1), but could plays a back-up solution in case of grid black-out. Taking advantage of the dynamic features of the grid electricity (cost, GWP) by sophisticated energy management systems to supervise the operation of the battery (see e.g. carbon-based load-levelling [6]), can still not offer operational benefits balancing the grey energy of the storage system itself [7]. Most of the time, a battery comes with a local RE generation to increase the onsite use of energy (case FB 2 and FB 3). Also, the battery is usually not only devoted to supplying the cooling system, but also the building electricity demand. This makes sense when the seasonal variation of cold demand occurs, since the viability (cost, primary energy and GHG emissions) of the battery is a function of its use. A method to define the minimum required batteries specifications for enabling sustainability are detailed in [6].

4.3. Flexibility given by thermal storage

Not easily implementable everywhere, especially in existing cooling systems, thermal storages are particularly adapted when chillers (see section 3.3) are involved. Therefore, it concern for the most part, application scaling from medium to big size. Thermal storage is placed downstream of the refrigeration machine sot that it is particularly interesting to limit the refrigeration capacity (and the harmful refrigerant amount) when encountering high peaks of cold demand (see case study in section 5). Heat losses are responsible for relatively low efficiency (see Table 1), which is why insulation for thermal

storage and piping systems is particularly important. Practically, implementing a thermal storage into a cooling system requires hydraulic works.

Two categories of thermal storages exist. The first is on sensible heat so the energy stored is directly proportional to the fluid temperature. The second involves the phase change of materials that are spread into a carrier fluid (see e.g.[8]). The resulting energy medium is called phase change material slurries, and the associated storage is based therefore mainly on latent heat. These man-made fluids are tailorable so their physical properties (e.g. melting point) are adjusted for their specific applications and have the specificity of very high energy density and could allow the release of cold at nearly constant temperature (see e.g. [9, 10]).

Table 1. Comparison between thermal and electricity storage technologies

Characteristics	Thermal storage		Electricity storage
	Sensible	latent	Li-Ion
Efficiency	50-90 (%) ^[11]	75-90 (%) ^[11]	90 (%) ^[12]
Lifetime	25 years ^[13]	25 years ^[13]	5.65E ⁻⁴ (%/kWh) ^[12]
GWP	32 ^{*b} (kg CO ₂ -eq) ^[13]	32 ^{*b} (kg CO ₂ -eq) ^[13]	0.021(kg CO ₂ -eq/kwh ^{el}) ^[12]
CEDnr	106 (kWh _{oil} -eq) ^[13]	106 (kWh _{oil} -eq) ^[13]	0.319(kWh _{oil} -eq/kwh ^{el}) ^[12]
Costs	0.1-10(Euro/kWh th) ^[11]	10-50(Euro/kWh th) ^[11]	176(Euro/kWh ^{el}) ^[14]
Storage capacity	1.16 (kWh th /K*m ³)	30-120 ^{*a} (kWh th /m ³) ^[10]	114 (Wh ^{el} /kg) ^[7]

^{*a}: heat of fusion only ^{*b}: storage tank of 600l without fluid

4.4. The choice between the different types of PF

The typology and technical specificities of the concerned refrigeration system often at least indicates which solution cannot be applied (e.g. battery in absorption chillers powered by gas as a fuel). If tolerated, flexibility through thermal inertia is the first strategy to consider, especially in the existing system, because it requires nothing other than some regulation thermostats enabling switching hysteresis. Often performance targets drive investments, and vice-versa. Financial aspects also guide the choice of adopting technologies which enable PF. Current research efforts tend to establish the advantages and drawbacks of each strategy. For example, researchers used a model to assess the cost performance of a district cooling system in Indian cities. Rather than for batteries, the choice of thermal storage enables larger profit (30%) and lower peak load at the same time [2].

5. Practical assessment of power flexibility in cooling systems

5.1. Power flexibility for minimization of the balancing energy

In European countries, electrical connection points are grouped in logically defined sets called balance groups. Each balance group must elaborate ahead of a global schedule made up of bought/sold energy volumes per quarter hour and must buy/sell energy accordingly. Day-after measurement results from energy meters are consolidated, and the difference between planned and measured energy volumes is computed. Balancing groups must pay penalties proportional to that difference named balancing energy. As precise forecasting is difficult, especially with intermittent renewables, means to limit balancing energy must be deployed. At any given time, a flexibility manager controls flexible processes to 1) minimise the energy balance within the current 15-minute period, and 2) correct the forecasted imbalance over the (typically 4) coming 15-minute periods.

A warehouse storing deep-frozen goods can be one of such flexible processes. Offering flexibility is a side function that must not jeopardize the main function (refrigeration). Hence, chillers are always controlled by the warehouse automation system. The flexibility management system may only give recommendations to the controller through a simple interface, as illustrated by Figure 5.

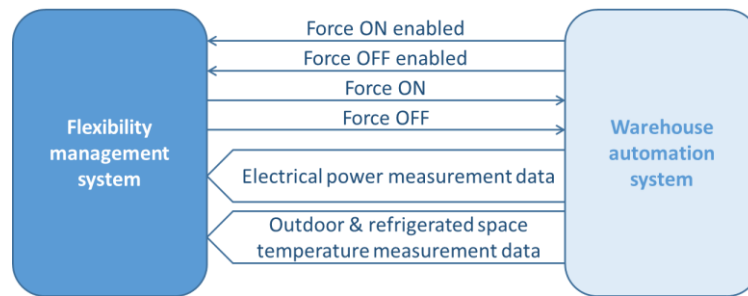


Figure 5. Interface between a deep-frozen warehouse automation system and a flexibility management system.

Thanks to two binary control signals (Force ON enabled, Force OFF enabled), the warehouse automation system indicates whether its chiller may be asked to consume full power or to be switched off. Only if the corresponding Force enabled signal is active, the flexibility management system may request cold generation with full power (Force ON) or request to disable cold generation (Force OFF). First tests have been performed on a Swiss warehouse where the refrigerated mass temperature may vary between $-26\text{ }^{\circ}\text{C}$ and $-20\text{ }^{\circ}\text{C}$. Cold generation could be interrupted during significant periods while keeping the refrigerated mass temperature within the allowed range, as illustrated in Figure 6.

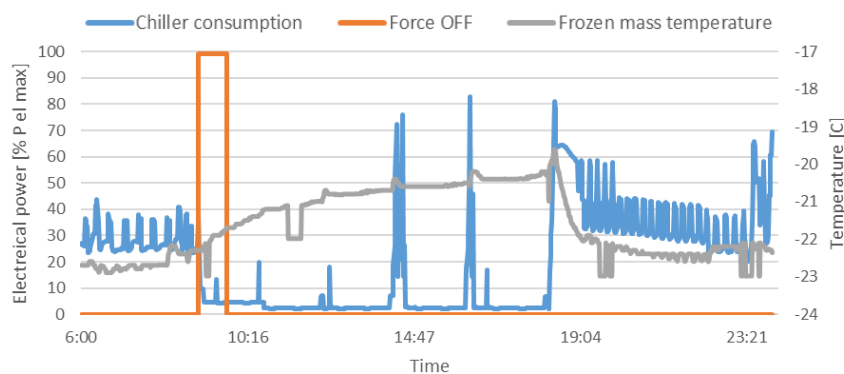


Figure 6. Test results on a Swiss deep-frozen warehouse.

The Force OFF signal was active (i.e. request to not generate cold) from 10:00 to 10:45. When the Force OFF signal stopped being active, the warehouse automation controller decided to let the mass temperature go up to the upper limit, before starting to generate cold again. During the Force OFF time, the saved power is about 30 kW. Hence, the saved energy during the 45 minutes Force OFF period is about 22.5 kWh, but it would have been possible to extend the Force OFF time up to 18:15, which would have saved 244.5 kWh. When the chiller restarted cold generation at 18:15, the electrical consumption became larger than average for one hour to compensate for the cold loss during the off time. This rebound effect must be accounted for in the flexibility management strategy. First results show that flexibility is usable in practice. It can be forecast reliably only if mass inlets and outlets are known. This can be achieved either by feeding the flexibility management system with logistics data or by applying artificial intelligence to discover mass inlets and outlets patterns.

5.2. Electrochemical batteries Vs. thermal storage

The second case study considers the project of a new hospital located in an urban area of Fribourg, central Switzerland. The architectural feasibility considers a building with a reference energy surface area of 4355 m². According to Swiss standards [15], the annual electricity needs for refrigeration are of 350 MWh/yr of thermal energy, concentrated from the middle of May until the middle of September. In this peculiar case, although no thermal tolerance can be expected from the users (the majority are sick people, and the professionals need to perform their job in good conditions). Electricity needs (heat pump for heating and domestic hot water, appliances, lighting, and other technical installation) of the building

account for 321 MWh/yr. A photovoltaic (PV) system (multi-Si n: 15.1%) covers 82% of the roof's surface (22x29m). The question is about the choice of the integration of an energy storage technology, especially the dilemma between electrochemical battery and/or thermal storage.

As the case study considers new construction with large instantaneous cooling needs, the priority is to cut the electrical power peaks of the cooling demand. This can't be achieved with an electrochemical battery placed before the cold production appliance. Consequently, we first proceed with the assessment of thermal storage, followed by the integration of electrochemical batteries. In both assessments and for considering the different interaction between the onsite RE production, energy storage and cold demand, dynamic simulations performed at the hourly time step are used to quantify the autonomy of the energy system (building and its refrigeration system) and the GHG emission balance related to the system's electricity use (See Table 2). The data used for the GWP of the grid mix are those provided in [16] and those of the weather recorder from the Posieux weather station for that same period (Year 2015).

5.2.1. Integration of thermal storage. The volume of the thermal energy storage is sized based on the daily thermal energy needs for the hottest day of the year (See Figure 7, $E_{th} = 45.5E9$ J) and the power of cold production, this last inversely proportional to the possible time of operation during a full day of service. Also, increasing cold power production reduces the necessity of a storage tank. The upper limit is described as the first alternative in Table 2.

In this case study, the different periods of operation are prioritized as a function of two indicators at building-owner and society level. They are, respectively, the cost of electricity (1st priority) and the global warming potential of electricity (2nd priority). Therefore, we limit the time of cold production operation at 18 hours during the day of the most important demand of the year (see Figure 8). On that basis, the cold power production is set at nominal capacity 608 kW with an Energy Efficiency Ratio (EER) of 4.2 value, reflecting current performance of the practice in Switzerland [17].

According to [8], the necessary volume of sensible storage would be of 620 m³ with a secondary loop operating at 8-12°C, and a safety factor for the tank of 1.2. An important reduction of the storage volume can be achieved by using phase change material slurries (from 90 to 260 m³, depending which PCMS is chosen [10]). With such a solution, the annual final energy spent on cooling power represents circa 20% of the final electricity consumption. This amount roughly corresponds to the same amount of yearly PV production placed on the maximum possible surface area of the roof (82 MWh/yr.).

5.2.2. Integration of battery. Cooling demand appears during the period May-September. During the other period, the battery, previously charged with excess PV production, can contribute to other needs of electricity of the building. The idea to size the battery storage capacity to erase the cooling demand from the grid supply actually does not work in this particular case study, at least during the day of the year presenting the highest cooling load (see Figure. 7). On that specific, the entire PV production is instantaneously and entirely self-consumed.

Implanting an electrochemical battery of 50 kWh of capacity (Li-Ion NMC technology) allows the onsite use of 6517 kWh/yr. As presented in Table 2, the low gain in autonomy combined with the investment cost [14], and the extra GHG emission related to the electricity used during the operational phase of the building, cannot justify the choice of implementing batteries in the building energy system. This statement becomes truer if the export of excess electricity to the surrounding grid is possible. An electrochemical battery would rather be appropriate if RE electricity generation would not be consumed instantaneously onsite. It is important to highlight that for specific buildings, having a specific time mismatch between PV generation and load demand could possibly lead to the profitability of battery energy storage installation [18].

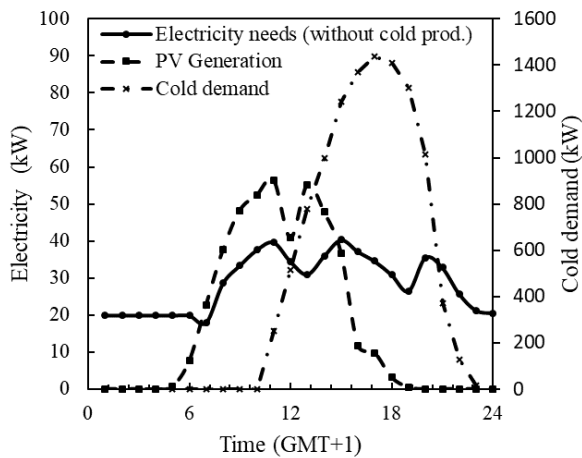


Figure 7. Cooling and electricity needs of the hospital, and PV production during the hottest day in the year 2015

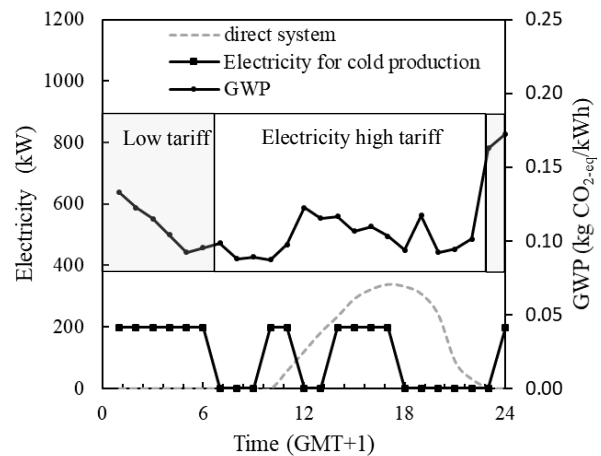


Figure 8. One-day operation of the cold production, associated with the GWP and costs characteristics of the grid mix

5.2.3. *Comparison of simulated performances.* Table 2 summarises the different alternatives discussed. Additionally, we address a scenario consisting of dispatched compressor-based split systems that would respond instantaneously to the cooling needs. This way of designing a cooling system would consist of installing extremely high cold-power production with no energy storage capacity at all.

Table 2. Comparison of the different investigated systems

Characteristics	Direct system	Thermal storage	Li-Ion Battery
Storage Volume (m ³)	0	90 ^{PCMS} – 620 ^{sensible}	440 (kg)
Electrical power cold production (kW)	340	200	200
Energy autonomy (%)	0	18.8	20.4
Indirect GHG emission (kg CO _{2-eq} /yr)	82'620	70'152	70'857

6. Conclusion

The unprecedented growth of cooling demand and its dramatic trend over the globe is driven by both global warming and the affordability of AC. The situation will soon become very problematic for electricity networks if no action is taken on the energy supply side (e.g. blackout of the power grid, extra GHG emissions for ensuring peak cold demand). The main objective of PF is to maximise the local use intermittent renewable that is planned to become the backbone of electricity supply, and to prevent high loads in the grid infrastructure. Among other obtainable benefits (i.e. lower primary energy and associated GHG emissions), the one of prior importance for the user is the possible financial gain since the grid operator manages the charge and energy fluxes in its energy network by applying time-dependent tariffs. The main possibilities for implementing flexibly into cooling systems are of three kinds: thermal tolerance at the customer side; implementing a thermal storage; or integrating an electrochemical battery that often comes when implementing onsite renewable energy production. The most affordable and, technically, the simplest way to integrate PF is unquestionably through thermal tolerance at the user side. But such an integration is not always possible. This is particularly the case in medicine and food preservation. For such applications, it could be particularly advantageous to implement latent cold storage tank with phase change slurries that deliver cold at a close-to-constant temperature. Moreover, compared to sensible storage, dedicated storage volume by PCMS can be drastically reduced. Electrochemical batteries are disadvantaged mainly due to their inability to cut down the necessary cooling power. Specific case studies address each of these three possible ways to integrate PF in cooling systems by quantitative assessments. The first case study considers thermal inertia of a

deep-frozen warehouse (between -26 °C and -20 °C). Experimental measurements show the possible time during which the cooling process can be stopped. A second case study treats the management of onsite renewable energy generation, mainly in the service of the refrigeration of a hospital. Based on dynamic simulations, the autonomy and indirect GHG emissions are assessed and help the implementation of thermal storage and/or batteries.

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