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Refrigerated warehouses as intelligent hubs to integrate renewable energy in industrial food refrigeration and to enhance power grid sustainability

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Abstract

Background

Independence from fossil fuels, energy diversification, decarbonisation and energy efficiency are key prerequisites to make a national, regional or continental economy competitive in the global marketplace. As Europe is about to generate 20% of its energy demand from Renewable Energy Sources (RES) by 2020, adequate RES integration and renewable energy storage throughout the entire food cold chain must properly be addressed.

Scope and approach

Refrigerated warehouses for chilled and frozen foods are large energy consumers and account for a significant portion of the global energy demand. Nevertheless, the opportunity for RES integration in the energy supply of large food storage facilities is often neglected. *In situ* power generation using RES permits capture of a large portion of virtually free energy, thereby reducing dramatically the running costs and carbon footprint, while enhancing the economic competitiveness. In that context, there exist promising engineering solutions to exploit various renewables in the food preservation sector, in combination with the emerging sustainability-enhancing technology of Cryogenic Energy Storage (CES).

Key Findings and Conclusions

Substantial research endeavours are driven by the noble objective to turn the Europe's Energy Union into the world's number one in renewable energies. Integrating RES, in synchrony with CES development and proper control, is capable of both strengthening the food refrigeration sector and improving dramatically the power grid balance and energy system sustainability. Hence, this article

aims to familiarise stakeholders of the European and global food preservation industry with state-of-the-art knowledge, know-how, opportunities and professional achievements in the concerned field.

Keywords: *food preservation, refrigerated warehousing, renewable energy, energy storage, cryogenics, low-carbon economy*

1. Introduction

The food sector is one of the most energy-intensive industrial branches. The amount of energy for cultivating, processing, packing and bringing the food to European citizens' tables accounts for about 17 % and 26 % of the EU's gross and final energy consumptions, respectively. The EU food industries are subject to important restructurings to make their activities more sustainable, through both increased investment in renewable energies and energy efficiency improvements. Since 2005 the food industry's energy consumption started to decline in terms both absolute amounts and energy intensity capable of producing more with use of less energy (JRC, 2015).

The food sector is generally considered as comparatively conservative because of its high reliance on fossil fuels and still limited penetration of renewable energies. Renewables account for some 7% of the energy used in food production and consumption, as compared with 15% of the overall energy mix. Fossil fuels account for almost 79% of the energy consumed by the food sector, while their share of the overall energy consumption is about 72%. Furthermore, about one fifth of food consumed in the EU is imported from regions where the renewable energy share is lower than 15% (JRC, 2015).

Consequently, the aim of this commentary article is to make stakeholders of the European and global food preservation industry more aware of the political framework and the state-of-the-art achievements in integrating renewable energies in refrigerated warehousing of foods. Special attention is paid to an emerging 'clean' and intelligent technology for cryogenic energy storage as a promising tool to enhance the sustainability of both industrial food refrigeration and power supply grids.

2. Food preservation sector in light of the European Energy Union and global energy policy

The EU is the biggest energy importer in the world, importing 53% of its energy at a cost of around EUR 400 billion a year. There is not yet a real European internal energy market: energy does not flow freely across borders and some parts of the EU (such as South-East Europe, the Iberian Peninsula and the Baltic States) remain isolated energy islands. Renewable energy is not fully integrated into the electricity system. Climate change cannot be halted by countries acting on their own. These are all examples of problems where coordinated action needs to be taken at the European level (EC, 2015c). Independence from fossil fuels, energy diversification, decarbonisation and energy efficiency are paramount challenges when putting substantial efforts to make the European economy much more competitive in the global marketplace. The EU also relies heavily on fuel and gas imports, which requires reform and reorganisation of Europe's energy policy into a new European Energy Union in order to pool resources, combine infrastructures and unite negotiating power *vis-à-vis* third countries (EC, 2015a, 2015b, 2016; Juncker, 2014).

The Political Guidelines announced by the European Commission's President Jean-Claude Juncker (2014) to be followed by the sitting European Commission define "*A Resilient Energy Union with a Forward-Looking Climate Change Policy*" as the third policy area tackled under the President's Agenda for Jobs, Growth, Fairness and Democratic Change. President Juncker pointed out that "... *we need to strengthen the share of renewable energies on our continent. This is not only a matter of a responsible climate change policy. It is, at the same time, an industrial policy imperative if we*

still want to have affordable energy at our disposal in the medium term. I strongly believe in the potential of green growth. I therefore want Europe's Energy Union to become the world number one in renewable energies" (Juncker, 2014). In accordance with the International Energy Agency (IEA, 2007), renewable sources are *"essential contributors to the energy supply portfolio as they contribute to world energy supply security, reducing dependency on fossil fuel resources, and provide opportunities for mitigating greenhouse gases"*.

As stated by the UN Secretary-General *"New and renewable sources of energy stand at the centre of global efforts to induce a paradigm shift towards green economies, poverty eradication and ultimately sustainable development"* (FAO, 2011). Renewable energy can be used throughout the food sector either directly to generate energy on-site or indirectly by integrating this energy into the existing conventional energy supply system. Reliable and affordable energy supply is an essential component for sustainable development (FAO, 2011, 2012; Fikiin & Stankov, 2015; United Nations, 2013). RES tend to be widely dispersed throughout agricultural areas. Wherever good renewable resources are available, farmers, fishermen, food processing and preservation businesses have various opportunities to install equipment for generating wind power, solar power, micro-hydropower, etc. In the future, it may also be commercially feasible to obtain electricity from sea and ocean resources. Solar thermal, biomass and geothermal resources, generated from decentralized facilities, can serve for both heating and cooling (FAO, 2011; Fikiin & Stankov, 2015; IPCC, 2011).

Sceptical voices often argue that (i) renewable energy technologies are more complicated and, therefore, less economically appealing than traditional sources of energy, and (ii) governments unjustifiably invest too much money and efforts to promote and sustain RES development. However, such negative views habitually disregard the massive amount of subsidies already invested in fossil fuels. In 2014 such subventions exceeded four times the overall subsidisation for renewable energy (IEA, 2015). Furthermore, large fuel importers bear a certain level of political uncertainty or risks because of their reliance on foreign resources. Although reshaping the energy infrastructure is a time- and resource-consuming venture, renewable energy technologies become thereby more cost-efficient and afford a significant competitive edge to the best adapted actors.

Given renewable energy technologies still remain burdensome, governments and public authorities employ policy instruments to promote relevant investments, thereby enhancing RES economic efficiency. Depending on location, these may include regulatory instruments, green certification schemes, financial incentives and other leverages. The broad variety of policy instruments in support of RES technologies was summarised by Fikiin & Stankov (2015). Industrial food refrigeration is one of the sectors which possess a huge but still unused potential for employing renewable energy technologies. Undoubtedly, food refrigeration deserves much more R&D efforts and investments as compared with some extravagant and fashionable applications whose environmental and economic impact is not so substantial (Maidment, 2014).

The worldwide market for industrial refrigerated storage of food, beverages and pharmaceuticals is large and constantly growing. Conventional refrigeration plants deliver temperatures in the range of -50°C to 20°C , while the refrigeration capacity of most plants commonly varies in the range of hundreds of kilowatts to dozens of megawatts. In practice, large electrically-driven vapour-compression refrigeration machines supply cold to a distribution network and operate with a COP ranging, most often, from 1.5 to 5 as a function of the machine design, evaporation temperature set point and other working (climatic) conditions. Large cooling towers are usually employed to dissipate condenser heat to the environment. According to the International Institute of Refrigeration (IIR, 2015), refrigeration (including air-conditioning) currently accounts for about 17% of worldwide electricity use, while over 80% of the global warming impact of refrigeration systems is due to this electricity use (IIR, 2007, 2015). Industrial refrigeration, comprising over 550 million cubic metres of cold storage space worldwide (IIR, 2015), is a major consumer of about 8% of the electrical power on a global scale (consistent with the circumstance that approximately 40% of the global food output require refrigeration).

Although a number of RES-assisted technologies exist for different refrigeration applications, many of them are still at rudimentary stages of development – either not commercially viable or only applicable for relatively small-scale systems. In any case, suitable RES integration in refrigerated food storage facilities provides cost-efficient means for: (i) reducing electricity consumption from the grid, and/or (ii) shifting refrigeration loads from peak to low consumption periods, thereby contributing to the overall balance of the power supply system and minimizing the environmental footprint of the refrigerated warehouses (Fikiin & Stankov, 2015).

3. Renewable energy integration in refrigerated warehousing

3.1. State of play and opportunities for implementing RES

A comprehensive study on different low-carbon technologies and strategies for RES integration in refrigerated warehouses was recently published by Fikiin & Stankov (2015). Refrigerating plants operating on diverse physical principles and renewables of different nature (solar, wind, geothermal, biogas, etc.) have been considered, as shown in Figure 1. Due attention was also paid to biogas-fuelled Combined Heat and Power (CHP) generation as an efficient option with low environmental impact. For instance, based on the findings of Fikiin & Stankov (2015), Table 1 summarises the features, advantages and drawbacks of a number of RES-driven refrigeration systems which can be used in food storage facilities or have a potential for future application.

The above-mentioned study revealed that the opportunities for RES integration in the energy supply of food cold storage facilities have often been overlooked. Although extensive information on RES research and developments for heating and power generation is available and easily accessible, RES-based implementations of industrial refrigeration systems are still scarce, while relevant information was fragmented and dispersed, until the recent work by Fikiin & Stankov (2015) filled this gap. Presently, the RES use for on-site power generation, especially through solar photovoltaic systems, appears to have gained more ground than RES-powered thermally driven refrigeration systems, as far as large refrigerated warehouses are concerned. There is significant progress in roof-mounted photovoltaic systems powering conventional vapour-compression refrigerating units (HelioSage, 2013; Fikiin & Stankov, 2015), an example of which can be seen in Figure 2. Such systems are convenient for simplification, unification and mass production, which enhance their market prospects, especially in the presence of substantial government incentives (ESTTP, 2008; Fikiin & Stankov, 2015).

3.2. Trends and prospects for wider uptake of RES technologies

Industrial installations, using heat from waste processes and RES to operate thermally driven refrigeration equipment, become competitive with the vapour-compression systems in areas where the electricity supply is unstable. For example, solar thermally driven refrigeration systems might employ roof- or ground-mounted, low- and medium-temperature solar collectors. However, very few such systems for large food warehouses have been implemented and studied so far. The rising price of electricity increases the interest in solar refrigeration, whose capital cost is still relatively high and prevents a wider market uptake. Thermally driven refrigeration systems need further improvements in order to become technically feasible and competitive for large refrigerated facilities, but the number of pilot and research projects is growing. Further research on equipment simplification, unification and cheapening is thus critically important (ESTTP, 2008; Fikiin & Stankov, 2015; RHC-Platform, 2014).

Solar, geothermal and biogas-driven CHP and trigeneration systems are still uncommon, but recent developments and research show promising trends. Solar-driven Stirling engines are being actively investigated and developed by several companies, while development of the organic Rankine cycle technology affords encouraging prospects for low-temperature solar and geothermal applications.

CHP and trigeneration systems driven by biogas present a valuable opportunity for food-processing factories which generate large amounts of food waste. Whilst on-site wind turbines and wind parks are still rare, in a smart grid context the so-called “*Night Wind*” strategy (Fikiin, 2015a; Van der Sluis, 2008) can substantially benefit both cold store operators and electric utilities (Butler, 2007; Fikiin & Stankov, 2015).

The attractiveness of RES-powered technologies steadily increases (even in periods of comparatively inexpensive conventional energy resources) due to the global concern about environmental sustainability, along with the reduced expenditure for RES equipment, resulting from R&D advancements and economies of scale. Fossil fuel costs fluctuate, with periodic peaks and drops, whose magnitude and duration, along with the import-related political implications, are difficult to predict (especially in the medium and long term). Although initial RES-related investments are commonly higher as compared with conventional technologies, renewables are virtually free, while RES equipment is associated with marginal running costs. For an individual market actor, the decision on whether, when and where to employ RES technologies is a matter of best-value trade-off analysis. The selection of the most appropriate RES technology for a particular industrial scenario should be based on (i) a thorough evaluation of RES availability and potential in the actual industrial site, (ii) dynamic modelling and simulation, along with a comprehensive life cycle analysis of the concerned RES system, and (iii) a survey of local government policies and incentives for RES, against the background of fossil fuel costs. Furthermore, knowledge-based optimisation and accurate energy management are indispensable to ensure that the RES system is operated in the most efficient manner.

Sometimes RES-related projects might be barely plausible to cold store operators, because of the difficulties associated with technical implementation and high initial investments. In addition, such projects need a pro-active and/or interactive approach towards the energy supply system, require increased organizational efforts and thus demand greater resulting involvement of the cold store operator. Hence, it might still appear to be more comfortable for the operator to act as traditional passive electricity consumer from the utility grid, especially in the short term.

In general, further research is still required to make RES-powered systems (currently viable for smaller-scale air-conditioning and cooling applications) competitive for larger refrigeration capacities typical for refrigerated warehouses. In the medium term, building up of experience and increased number of market actors should significantly enhance the technical and economic performance of the concerned technologies (Fikiin & Stankov, 2015).

4. Integration of renewables through an innovative technology for cryogenic energy storage

Intermittent supply is a major obstacle to the renewable power market (Boie, Fernandes, Frías, & Klobasa, 2014). Renewables are fickle sources, prone to overproducing when demand is low and failing to meet requirements when demand peaks (Inage, 2009). Integration of solar, wind and other distributed RES in the power grid is rather challenging, especially for traditional centralised grids with top-down structure. Grid balancing problems are common for both developed and developing economies worldwide. Implementing the so-called “*Smart Grids*” concept needs to make a transition from the traditional top-down approach of power supply toward more sophisticated (distributed, controllable, flexible and interactive) systems for electricity generation, transmission, distribution and consumption.

Refrigerated warehouses provide an ideal industrial environment to take advantage of RES technologies by using ‘*passive*’ and ‘*active*’ methods of Large-scale Energy (thermal and grid) Storage (LES), enabling on-site storage of renewable energy during periods of high generation and its use (and/or return to the power grid) at peak demands, thereby balancing the power grid. Hence, RES involvement fosters the LES developments and *vice-versa*, i.e. the RES and LES technologies

are mutually enabling and should be deployed in parallel (Fikiin, 2015b; Fikiin & Stankov, 2015). Recovery of waste energy from cooling and heating substantially enhances the LES round-trip efficiency and RES desirability, which is another driver for implementing RES technologies in the food processing and preservation industry worldwide (CryoHub, 2015). Energy storage (including LES) may be based on diverse underlying physical principles, e.g. making use of heat or cold accumulation, hydroelectricity, compressed air, cryogenic substances, flywheels, supercapacitors, superconducting magnets, electrochemical cells and batteries, fuel cells, etc. (CLCF, 2013).

Amongst the numerous methods to store energy, Cryogenic Energy Storage (CES) is a known, but still rather undeveloped and unexploited thermal energy storage principle, which is coming again in favour due to its attractive features and advantages (Ding *et al.*, 2015; Brett & Barnett, 2014; CLCF, 2013; CLCF & LAEN, 2013). At low power demand, CES systems use electricity from RES or the grid to liquefy air (as a mixture or separate nitrogen, oxygen and argon) and to store the liquefied cryogen in a large insulated vessel at very low (cryogenic) temperatures. It can be recalled that, at atmospheric pressure, liquid nitrogen (constituting approx. 78 % of the air content) has a boiling point of $-195.8\text{ }^{\circ}\text{C}$, while liquid oxygen (approx. 21 % of the air content) boils at $-183\text{ }^{\circ}\text{C}$. The latent heat of vaporization is 200 kJ/kg for N_2 and 213 kJ/kg for O_2 . In several applications, a sensible heat of up to 160 kJ/kg can also be exploited. CES is a promising technology enabling on-site storage of RES energy during periods of high generation and its use at peak grid demand. Thus, CES acts as grid energy storage, whereas at peak demands liquid cryogen is boiled (with an over 700-fold expansion in volume) to drive a turbine and to restore electricity to the grid.

Hence, the principle of Cryogenic Energy Storage (CES) is simple and logical:

- During periods of low power demand and low energy price, a cryogenic gas is liquefied and stored in a well-insulated vessel (charging period).
- During times of high power consumption and high energy price, the liquefied cryogen is pumped and expanded to drive a generator of power which is restored to the electrical grid (discharging period).

To date, CES applications have been rather limited by the poor round-trip efficiency (ratio between energies retrieved from and spent for energy storage) due to unrecovered energy losses. In fact, the liquefaction of a unit mass of cryogen currently consumes much more energy than its evaporation can deliver. Adequate R&D endeavours must therefore address this issue by maximising the RES input, cryogenic cold utilisation, waste heat recovery, proper control and system optimisation.

Automotive engines powered by cryogenically stored energy have already been tried and tested in the past. In 1899 such a car engine was designed and produced by the Liquid Air Company of Boston, Massachusetts (CLCF, 2013; CLCF & LAEN, 2013). The first cryogenic automobile was demonstrated by its inventor Hans Knudsen at a London motor show in 1902 and has earned a variety of rather controversial appraisals, ranging from lauds and admirations up to charges of fraud and allegations that it was just a modified Locomobile steamer. Over 100 years later, the British inventor Peter Dearman patented in 2001 the Dearman Engine designed to improve the efficiency of cryogenically powered applications (English, 2013; CLCF, 2013; CLCF & LAEN, 2013).

Recent R&D activities around the world, focused on CES deploying and advancing, can briefly be summarised as follows:

- Mitsubishi Heavy Industries (*Japan*) tested and reported a utility-scale CES application (Kishimoto, Hasegawa, & Takahisa, 1998).
- Highview Power Storage (*UK*) tested a pilot CES-RES system (350 kW/2.5 MWh) from 2011, which was reported to achieve a round-trip efficiency of 8%, with potential to reach a desirable net efficiency of 50-70% through a larger-scale equipment (over 20 MW), if available cold and waste heat are recycled (Morgan, Nelmes, Gibson, & Brett, 2015).

- Dearman (*UK*) developed and commercialised the Dearman engine with emphasis on refrigerated transport applications (Tovey, 2015).
- Linde Gas and Hitachi Power Europe (*Germany*) examined the CES mechanism in parallel and in comparison with the compressed air energy storage findings (Stover, Rehfeld, Alekseev, & Stiller, 2014).
- Birmingham Centre of Cryogenic Energy Storage (*UK*) housed a state-of-the-art facility for R&D in CES systems, including laboratories and a demonstration plant (University of Birmingham, 2016).

While the aforementioned pioneering studies focused primarily on power generation issues, Fikiin (2015b) launched recently the idea to apply CES in the territory of industrial refrigerated warehouses, thereby capturing and utilising the vast amount of cryogenic cold released when boiling the stored liquid cryogen (in combination with RES integration and waste heat recovery). This extra cooling potential eases the functioning of existing refrigeration plants by providing substantial part of the refrigeration capacity needed to maintain the desired low-temperatures in storage warehouses for chilled or frozen foods (Fikiin, 2015b). Furthermore, integrating CES into food processing or preservation facilities is a novel and attractive means for fostering the growth of the RES sector, revealing also a substantial potential to improve efficiency (CryoHub, 2015; Fikiin, 2015b).

On these grounds a pan-European consortium of 14 partners from industry and academia (including universities, research institutions, SMEs, large industries and international organisations) from five EU countries has recently elaborated an EU Horizon 2020 Project entitled “*CryoHub – Developing Cryogenic Energy Storage at Refrigerated Warehouses as an Interactive Hub to Integrate Renewable Energy in Industrial Food Refrigeration and to Enhance Power Grid Sustainability*” (CryoHub, 2015). This innovation action has been approved by the European Commission and earned an EU grant of over 7 MEUR to perform a 3.5-year work programme. The project is coordinated by the London South Bank University and commenced in early 2016. Figure 3 illustrates the underlying CryoHub concept for employing renewable energy to liquefy and store cryogens, capable of balancing the power grid, while meeting part of the cooling demand of a refrigerated food warehouse and recovering the waste heat from its equipment and components.

The CryoHub innovation project investigates large-scale CES and extends its potential by applying the stored energy for both cooling and electricity generation. CryoHub is designed to maximise the CES effectiveness by means of a consistent RES-assisted cycle of cryogen liquefaction, storage, distribution, efficient use and power regeneration, which enhances the operation of conventional refrigeration plants and resulting overall system efficiencies (Figure 4). Preliminary estimates implied that, applying RES-powered CES to some 10% of 5000-6000 large refrigerated facilities EU-wide, the annual reduction in CO₂e emissions might exceed 9 Mt across EU28 (CryoHub, 2015).

5. Conclusions and further research

This viewpoint article outlines various RES integration opportunities for the food refrigeration sector and explains how a conventional refrigerated food warehouse can be converted from a simple power consumer to a smart energy hub, which interacts with the electricity supply system by employing RES and an innovative CES-based technology named CryoHub. Thus, the advantages of both ‘*mechanical*’ and ‘*cryogenic*’ refrigeration are synergistically brought together (without giving preference to any of these two principles competing long ago in the food processing and preservation industries).

Refrigerated warehouses for chilled and frozen food commodities are large electricity consumers, possess powerful installed capacities for cooling and heating and waste substantial amounts of heat.

Such facilities provide the ideal industrial environment to demonstrate, elaborate and advance the emerging CES technology by enhancing substantially its round-trip efficiency. Thus, RES integration, in synchrony with CES development and intelligent control, is capable of both strengthening the refrigeration sector itself and improving dramatically the power grid balance and energy system sustainability. The CryoHub concept for synergistic use of CES and RES might overcome most of the existing technology barriers at one go, thereby paving the way for broader market prospects for a CES-based economy of the future.

To achieve the above-mentioned goal, a number of relevant objectives are currently addressed by the international CryoHub consortium, e.g.: (i) determining key processes and unit operations to take advantage of CES in a common refrigerated warehouse and identifying how stored cryogenic cold could be integrated in the best possible way; (ii) exploring the synergistic and mutually-enabling action of CES and RES-based technologies in refrigerated food warehousing; (iii) determining the energy and carbon savings which CES could achieve, against the background of conventional technologies; (iv) identifying engineering solutions to consolidate a CES system into a typical warehouse refrigeration plant for performance optimisation and efficiency enhancement; (v) developing software for automated decision-support and management of CES and cryogen expenditure as a function of warehouse, RES and grid behaviour, environmental conditions, energy demand, availability and price variation (depending on tariff plans negotiated and/or fluctuations on the stock market); (vi) building a CES demonstration plant, validating and demonstrating the CES performance for a representative refrigerated warehouse; (vii) elaborating a strategy for CES implementation in the food refrigeration sector across Europe, etc. Simultaneously, novel and promising CES applications beyond the food sector are actively sought.

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Acronyms

CES	Cryogenic Energy Storage
CHP	Combined Heat and Power
COP	Coefficient of Performance
EU	European Union
IEA	International Energy Agency
IIR	International Institute of Refrigeration
LES	Large-scale Energy Storage
RES	Renewable Energy Sources
R&D	Research and Development

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Figure Captions

Figure 1. Various options to integrate RES in the energy supply of refrigeration systems for food storage facilities (Adapted from Fikiin & Stankov, 2015).

Figure 2. The 9 MW solar park on the rooftop of the Holt Logistics refrigerated warehouse, Gloucester Marine Terminal, New Jersey (Thurston, 2012; Pereyra Boue, 2014).

Figure 3. The refrigerated warehouse as an interactive hub to integrate and store renewable energy and to balance the power grid (Adapted from Fikiin, 2015b; CryoHub, 2015).

Figure 4. Possible arrangement of a refrigerated food warehouse with synergistic operation of RES and CES (Adapted from Fikiin, 2015b).

Table Caption

Table 1. Several RES technologies with actual or potential use in refrigerated food warehousing.

Figures

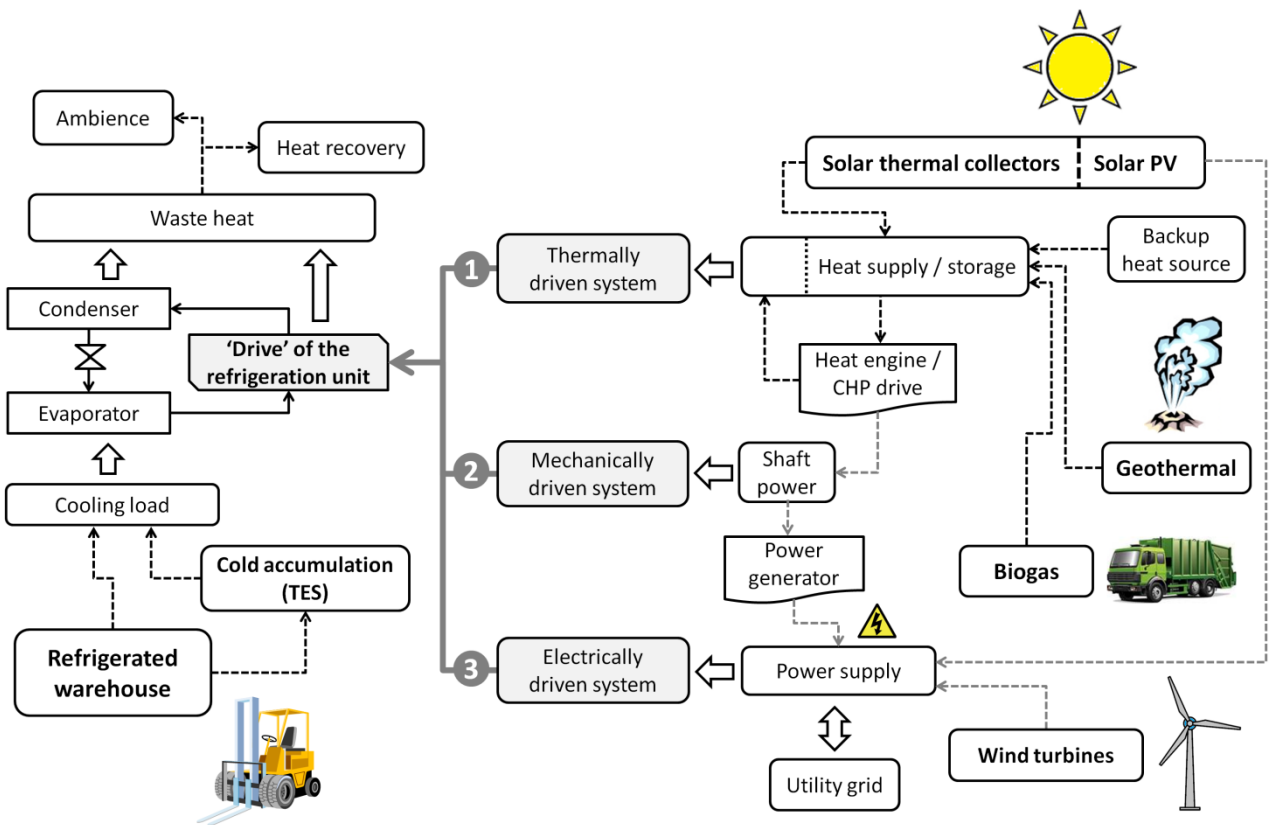


Figure 1



Figure 2

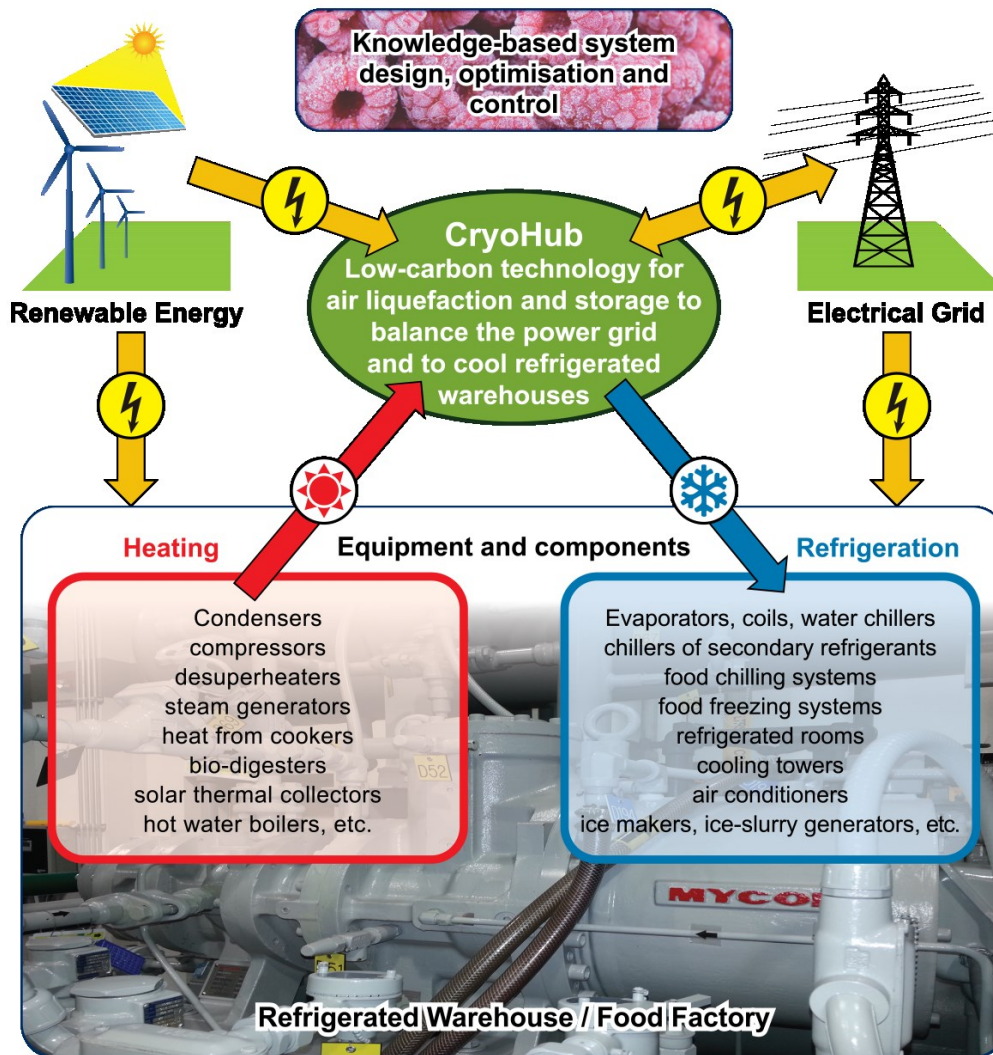


Figure 3

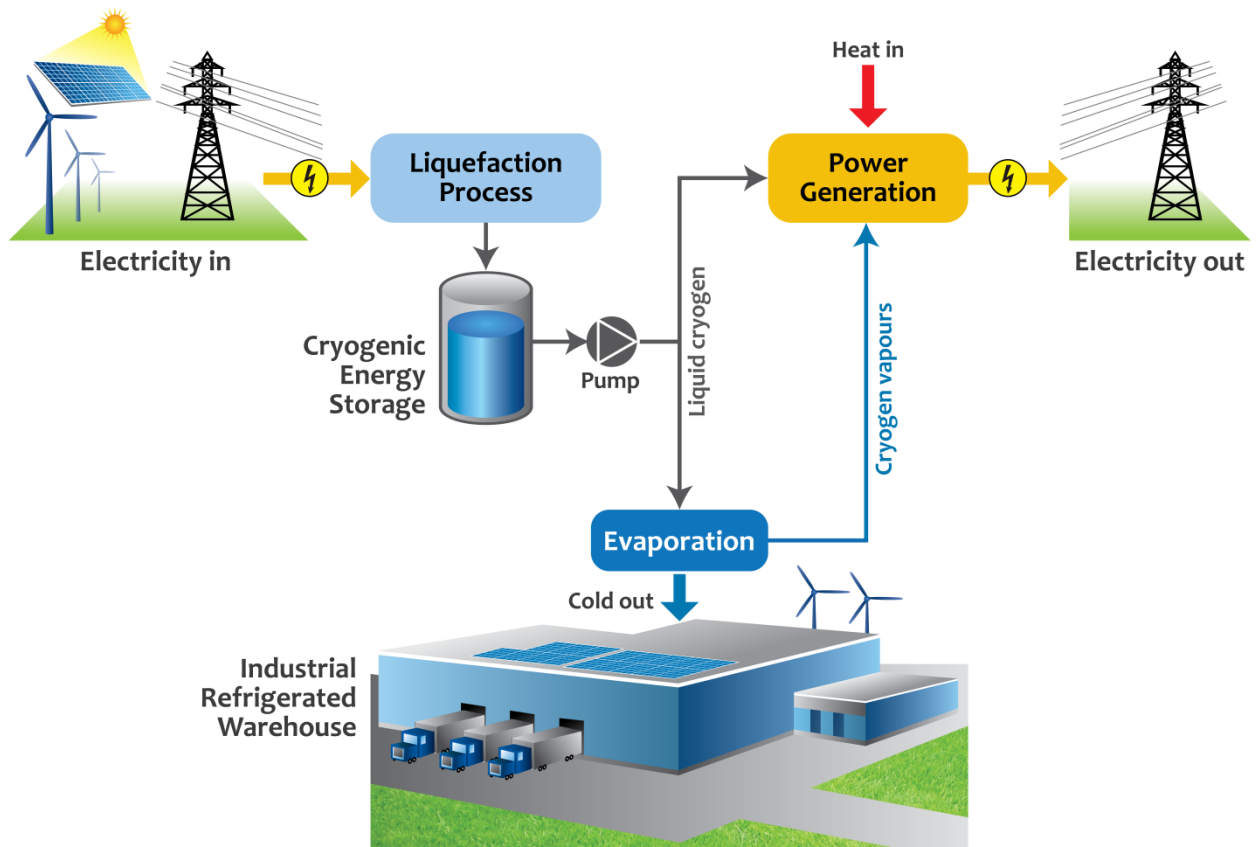


Figure 4

Tables

Table 1. Several RES technologies with actual or potential use in refrigerated food warehousing.

RES Technology	Basic Features	Advantages	Drawbacks
Solar sorption systems	<ul style="list-style-type: none"> Heat supplied by solar thermal collectors, used to drive an absorption or adsorption refrigeration system. Typical overall system efficiency of about 40%. 	<ul style="list-style-type: none"> Low auxiliary energy consumption and environmental impact. Easy maintenance. Few moving parts, reduced noise and vibrations. 	<ul style="list-style-type: none"> Relatively small number of manufacturers Limited experience with large-scale food storage facilities, which needs more R&D for system optimisation High initial costs.
Solar thermo-mechanical systems	<ul style="list-style-type: none"> Heat supplied by solar thermal collectors, converted to mechanical work by a heat engine. Mechanical work used to drive the compressor of a vapour-compression refrigeration system. Typical overall system efficiency of about 5%. 	<ul style="list-style-type: none"> Potentially competitive when using concentrating solar collectors with tracking systems to provide high temperatures for large-scale refrigeration applications (over approx. 3500 kW). 	<ul style="list-style-type: none"> Very low energy conversion efficiencies. Limited applications (no example is available for large food storage facilities). Quite limited number of large manufacturers. High initial costs.
Solar photovoltaic systems	<ul style="list-style-type: none"> Solar radiation converted by PhotoVoltaic (PV) modules into direct current used directly (or transformed to alternating current) to run electrically driven refrigeration systems. Typical lifetime of solar PV modules in the range of 20-25 years. Typical overall system efficiency of about 35%. 	<ul style="list-style-type: none"> Availability of large flat roofs of storage warehouses, convenient to place PV modules generating power on-site. Well coinciding peaks of warehouse power demand and solar irradiation. PV-generated power saleable to the utility grid at beneficial prices. Relatively high number of recent applications in large refrigerated warehouses (mostly based in the USA). 	<ul style="list-style-type: none"> Low energy conversion efficiencies. Still high installed costs and long payoff periods (substantially alleviated via beneficial policy instruments of the local authorities).
Wind turbines	<ul style="list-style-type: none"> Wind energy converted to alternating current to run electrically driven refrigeration systems. Typical turbine lifetime in the range of 20-30 years. 	<ul style="list-style-type: none"> Less expensive than solar PV systems (on a levelized basis) with similar operational lifetime. Generated power saleable to the utility grid at beneficial prices. Beneficial application of the 'Night wind' control strategy. 	<ul style="list-style-type: none"> Large and expensive turbines, more efficient for large-scale utility generation systems. Limited on-site applications in food storage facilities.
RES-driven combined heat and power (CHP) systems	<ul style="list-style-type: none"> Heat engine driven by RES-supplied heat (solar, geothermal, biofuels). Various 'trigeneration' options (e.g. power-driven vapour-compression refrigeration systems, and/or heat-driven sorption refrigeration systems). Overall efficiency of a solar-driven CHP system (neglecting the refrigeration system if any) expected to exceed 60%. 	<ul style="list-style-type: none"> Opportunities for use of on-site produced biogas (via anaerobic digestion of biodegradable waste or wastewater treatment facilities). Commercial availability of suitable gas turbine engines. Applicability of both Stirling and Rankine cycle heat engines, specifically designed for use with solar concentrating collectors. Commercial availability of organic Rankine cycle systems with various capacities, operating in a wide range of heat source temperatures (74-350°C) and integrative in low-temperature solar and geothermal CHP systems. 	<ul style="list-style-type: none"> Very few existing applications for food storage warehouses (more experience with biogas systems). Complex design and operation. Need for large areas for equipment installation. High capital and maintenance costs and long payback periods (in absence of government incentives).

Highlights

- Food refrigeration should take advantage of advanced renewable energy technologies.
- Efficient integration of renewables crucially depends on the energy storage modes.
- Food cold stores are perfect to enhance the efficiency of cryogenic energy storage.
- Refrigerated warehouses may act as interactive energy hubs within the power grids.

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