Large scale energy storage

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

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691761.

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Report on refrigerated food facility mapping

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Distribution List

- On the project Portal
- On the CryoHub Intranet (http://cryohub.psutec.com/)

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Acronyms

ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
CES	Cryogenic Energy Storage
ECSLA	European Cold Storage and Logistics Association
GCCA	Global Cold Chain Alliance
IARW	International Association of Refrigerated Warehouses
IIR	International Institute of Refrigeration
LAES	Liquid Air Energy Storage
RES	Renewable Energy Sources

1. Executive summary

The present task WP2.1 and its resulting deliverable D2.1 addressed the energy consumption of the large EU refrigerated warehouses (cold stores) and food factories and their location on the EU map. For that purpose, a dedicated web-based survey was developed, which was designed to be simple and takes less than 5 minutes to complete. Thus, the following information was collected: (i) location of refrigerated warehouse or food factory; (ii) approximate size of refrigerated facilities; (iii) average and peak electrical input power to the facility; (iv) possible waste heat generation (if information is available); (v) availability of RES currently installed on site and their maximum capacity; (vi) whether RES could potentially be installed on site; etc. The electronic survey was also translated from English into French, German, Spanish, Italian and Bulgarian languages. In spite of the huge efforts to promote the survey Europe-wide by using numerous international organisations, professional networks, specialised periodicals, conference events and global media, the survey received a rather modest public response so far. This might be caused by the conservatism in the sector and the general reluctance of warehouse operators to share their energy data. Another reason could be the need to use the survey during several years, while D2.1 is to be reported by the end of month 10 after the project started. In such a longer period, the CryoHub awarding system could take effect as more warehousing companies will have the chance to enjoy the status of a *'CryoHub Champion'* and to obtain a relevant certificate, thereby testifying their innovation friendliness and environmental credentials.

Nevertheless, the task was successfully performed and delivered due to the information collected from national and EU authorities, and international cold chain associations, such as Global Cold Chain Alliance (GCCA), European Cold Storage and Logistics Associations (ECSLA), EU Directorate-General for Health and Food Safety (DG SANTE), ministries, etc. Energy consumption data were partially available only from a few national ministries of EU countries. Hence, along with the warehouse localisations, partners focused on collecting data about their storage capacities (in m^2, m^3, tonnes or pallet number). By using specific energy consumption values, previously determined as part of the ICE-E project, the capacity data were easily converted to indicative power consumption figures, whose accuracy is fairly sufficient for a Europe-wide data gathering exercise with such a broad coverage and large scope. Only scarce information for isolated cases was readily available on the waste heat and the variation of power consumption with time, which serves for an orientation but is of secondary and not crucial importance when accessing the opportunities for integrating RES and the CryoHub technology in refrigerated food facilities. Three partners (LSBU, IRST and TUS) handled and coordinated the data collection process for different groups of countries: **(i)** LSBU (for Belgium, Denmark, Finland, Germany, Ireland, Luxemburg, the Netherlands, Sweden and UK); **(ii)** IRST (for Austria, France, Italy, Malta, Portugal and Spain); and **(iii)** TUS (for Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Greece, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia and Slovenia).

ArcGIS was selected as mapping software and relevant energy consumption maps were produced by CRAN for refrigerated food facilities in EU 28 as a whole and EU member countries separately. Furthermore, to facilitate the further analysis the EU countries were mapped in the following groups: (i) Benelux (Belgium, the Netherlands and Luxemburg); (ii) Central and Eastern Europe (Bulgaria, Croatia, Czech Republic, Hungary, Poland, Romania, Slovakia and Slovenia); (iii) Germany and Austria; (iv) Mediterranean countries (Cyprus, France, Greece, Italy, Malta, Spain and Portugal); (v) Nordic and Baltic EU countries (Denmark, Estonia, Finland, Latvia, Lithuania and Sweden); (vi) United Kingdom and Ireland. The obtained database was filtered so as the maps elaborated indicate only large refrigerated facilities spending over 500 kW of electrical power.

Obviously, task WP2.1 and the present deliverable D2.1 form an essential input to the next tasks and resulting deliverables of WP2, focusing on *“Renewable energy mapping”* and *“Potential opportunities for CryoHub in Europe”.* In addition, the information obtained is vital for WP 3 *“Current and future benefits of CryoHub”,* WP 8 “*Market barriers and strategies”* and WP 10 *“Energy policy and future integration”.* Substantial progress was also registered in determining the hosting company of the CryoHub Demonstration site (*Golden CryoHub Champion*) which is indispensable for WP 11 *“CryoHub Demonstration”.*

2. Context

2.1. CryoHub overview

The CryoHub innovation project investigates and extends the potential of large-scale Cryogenic Energy Storage (CES) and applies the stored energy for both cooling and energy generation. By employing Renewable Energy Sources (RES) to liquefy and store cryogens, CryoHub balances the power grid, while meeting the cooling demand of a refrigerated food warehouse and recovering the waste heat from its equipment and components.

The intermittent supply is a major obstacle to the RES power market. In reality, RES are fickle forces, prone to over-producing when demand is low and failing to meet requirements when demand peaks. Europe is about to generate 20% of its required energy from RES by 2020, so that the proper RES integration poses continent-wide challenges.

The CES, and particularly the Liquid Air Energy Storage (LAES), 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 (GES), where cryogen is boiled to drive a turbine and to restore electricity to the grid. To date, CES applications have been rather limited by the poor round trip efficiency (ratio between energies spent for and retrieved from energy storage) due to unrecovered energy losses.

The CryoHub project is therefore designed to maximise the CES efficiency by recovering energy from cooling and heating in a perfect RES-driven cycle of cryogen liquefaction, storage, distribution, efficient use and power regeneration. 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 advance and demonstrate the LAES benefits.

CryoHub could thus resolve most of the above-mentioned problems at one go, thereby paving the way for broader market prospects for CES-based technologies across Europe.

2.2. Overview of Work Package 2

Work Package 2 “*Refrigerated Warehouse and Renewable Energy Mapping*” has three main objectives:

- To map locations of large refrigerated warehouses and food factories in Europe (over 0.5 MW average power input) and their power usage, looking also at possible waste heat generation and power consumption profiles over time.

- To map whether these stores have access to RES on site or locally (within 1 km). Potential for stores without access to RES to install RES.
- To determine the potential for CryoHub application with resulting benefits (to be further determined in WP3).

2.2.1. Purpose of deliverable

In accordance with the Grant Agreement, the present deliverable D2.1 is dedicated to the **mapping of the location and the power consumption of large refrigerated food facilities across Europe** (with power consumption over 500 kW). In particular, refrigerated warehouses or food factories for chilled and frozen food commodities were considered, along with facilities possessing mixed capacities for chilled and frozen products.

D2.1 is of paramount importance for D2.2 *"Report on RES mapping"* and D2.3 *"Report on potential opportunities for CryoHub in Europe"* to map the renewable energy installations close (in the vicinity of 1 km) to the refrigerated food facilities, thereby identifying and analysing opportunities for further application of the CryoHub concept throughout Europe. Furthermore, D2.1 is vital for WP3 *"Current and future benefits of CryoHub",* WP 8 *"Market barriers and strategies"* and WP 10 *"Energy policy and future integration".* In addition, D2.1 plays a very substantial role when determining the right company to host the CryoHub Demo site (*Golden CryoHub Champion*), addressed by WP 11 *"CryoHub Demonstration".*

A rather substantial amount of the data gathered are completely new and are reported for the first time. This, the present report constitutes a step forward, as compared with other similar databases (e.g. the Global Cold Chain Alliance Directory), as further detailed in Section 3.3.

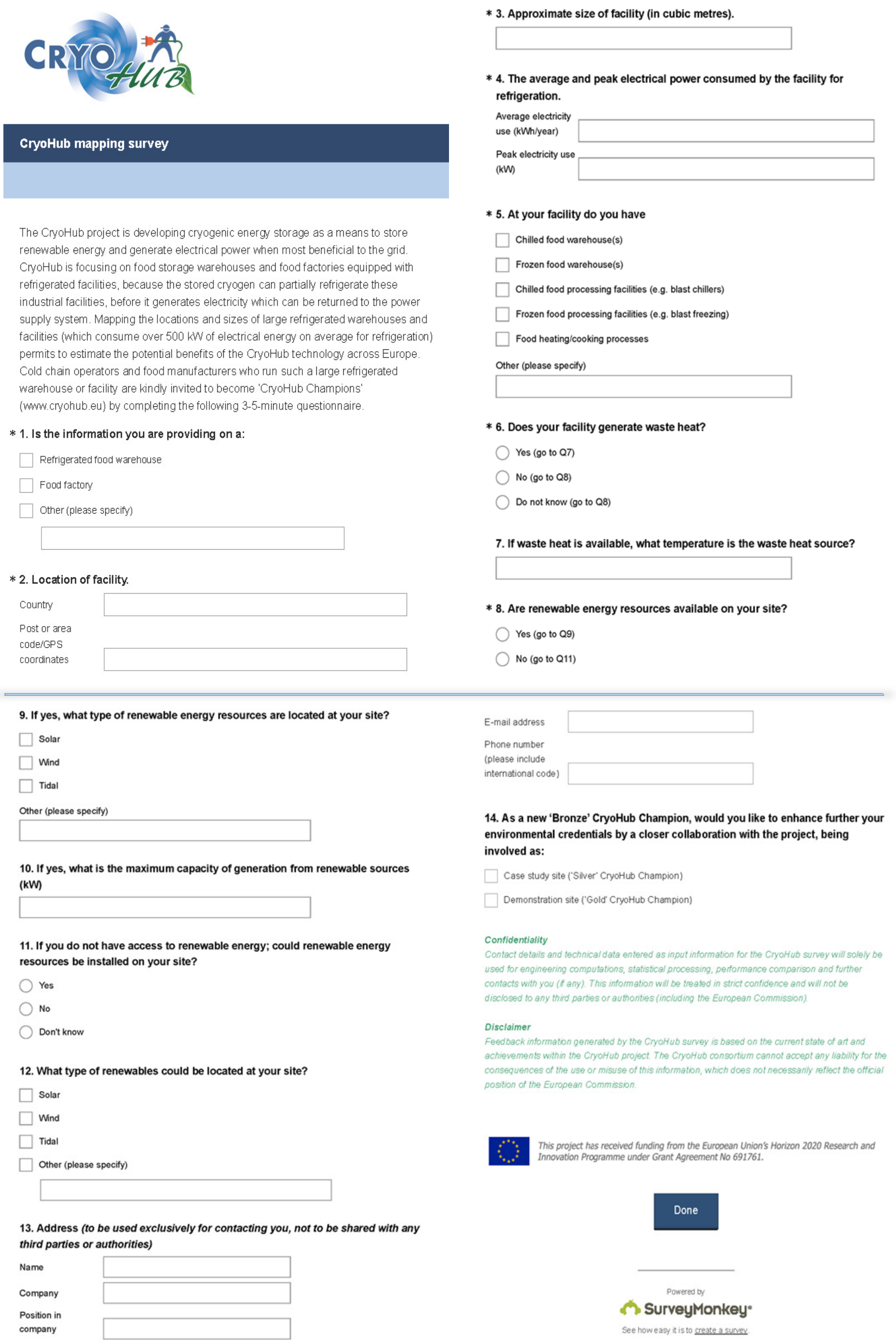
3. Methodology

Methodologically, several main approaches have been employed: **(i)** data collection by using a dedicated on-line energy mapping survey, **(ii)** energy consumption information taken directly from national authorities or cold chain associations; and **(iii)** deriving energy usage figures from existing capacity data for refrigerated food facilities by means of previously determined specific energy consumptions of refrigerated warehouses with various purposes, as detailed hereafter.

3.1. CryoHub energy mapping survey

3.1.1. Elaborating the survey as a data collection tool

The CryoHub energy mapping survey for large refrigerated food warehouses or food factories equipped with refrigeration facilities was developed and published in the English language on https://www.surveymonkey.co.uk/r/cryohub. The questionnaire contains 14 queries reflecting the objectives of WP2, as detailed in Figure 1.



CryoHub mapping survey

The CryoHub project is developing cryogenic energy storage as a means to store renewable energy and generate electrical power when most beneficial to the grid. CryoHub is focusing on food storage warehouses and food factories equipped with refrigerated facilities, because the stored cryogen can partially refrigerate these industrial facilities, before it generates electricity which can be returned to the power supply system. Mapping the locations and sizes of large refrigerated warehouses and facilities (which consume over 500 kW of electrical power on average for refrigeration) permits to estimate the potential benefits of the CryoHub technology across Europe. Cold chain operators and food manufacturers who run such a large refrigerated warehouse or facility are kindly invited to become 'CryoHub Champions' (www.cryohub.eu) by completing the following 3-5-minute questionnaire.

* 1. Is the information you are providing on a:

- Refrigerated food warehouse
- Food factory
- Other (please specify)

* 2. Location of facility.

Country

Post or area code/GPS coordinates

* 3. Approximate size of facility (in cubic metres).

* 4. The average and peak electrical power consumed by the facility for refrigeration.

Average electricity use (kWh/year)

Peak electricity use (kW)

* 5. At your facility do you have

- Chilled food warehouse(s)
- Frozen food warehouse(s)
- Chilled food processing facilities (e.g. blast chillers)
- Frozen food processing facilities (e.g. blast freezing)
- Food heating/cooking processes

Other (please specify)

* 6. Does your facility generate waste heat?

- Yes (go to Q7)
- No (go to Q8)
- Do not know (go to Q8)

7. If waste heat is available, what temperature is the waste heat source?

* 8. Are renewable energy resources available on your site?

- Yes (go to Q9)
- No (go to Q11)

9. If yes, what type of renewable energy resources are located at your site?

- Solar
- Wind
- Tidal

Other (please specify)

10. If yes, what is the maximum capacity of generation from renewable sources (kW)

11. If you do not have access to renewable energy; could renewable energy resources be installed on your site?

- Yes
- No
- Don't know

12. What type of renewables could be located at your site?

- Solar
- Wind
- Tidal
- Other (please specify)

13. Address *(to be used exclusively for contacting you, not to be shared with any third parties or authorities)*

Name

Company

Position in company

E-mail address

Phone number (please include international code)

14. As a new 'Bronze' CryoHub Champion, would you like to enhance further your environmental credentials by a closer collaboration with the project, being involved as:

- Case study site ('Silver' CryoHub Champion)
- Demonstration site ('Gold' CryoHub Champion)

Confidentiality

Contact details and technical data entered as input information for the CryoHub survey will solely be used for engineering computations, statistical processing, performance comparison and further contacts with you (if any). This information will be treated in strict confidence and will not be disclosed to any third parties or authorities (including the European Commission).

Disclaimer

Feedback information generated by the CryoHub survey is based on the current state of art and achievements within the CryoHub project. The CryoHub consortium cannot accept any liability for the consequences of the use or misuse of this information, which does not necessarily reflect the official position of the European Commission.

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Done

Powered by SurveyMonkey

See how easy it is to create a survey

Figure 1. Web-based CryoHub mapping survey.

3.1.2. Translation to national languages

Translated versions of the survey were published in 5 EU languages, as follows:

- German: https://www.surveymonkey.co.uk/r/cryohubDE
- French: https://www.surveymonkey.co.uk/r/cryohubFR
- Bulgarian: https://www.surveymonkey.co.uk/r/cryohubBG
- Spanish: https://www.surveymonkey.co.uk/r/cryohubES
- Italian: https://www.surveymonkey.co.uk/r/cryohubIT

3.1.3. Promoting the survey worldwide

The CryoHub survey was actively promoted by means of the established channels of a number governmental and non-governmental professional organisations, editorial boards and networks, networks. For instance, the following stakeholders' organisations were approached and provided with information about the survey.

- ☑ **ECSLA** (*European Cold Storage and Logistics Association*) and relevant national associations, **GCCA** (*Global Cold Chain Alliance*), **IAR** (*International Academy of Refrigeration*), **GCI** (Green Cooling Initiative), **IIAR** (*International Institute of Ammonia Refrigeration*), **ASHRAE, AFF, EHPA, EPEE, AREA, E&P, Eurocommerce, Eurovent, Eurammon, etc.**
- ☑ **FoodDrink Europe, EFFoST** (*European Federation of Food Science and Technology*), **ETPs** (*European Technology Platforms*) *'Food for Life',* and *'Renewable Heating and Cooling',* **EHEDG** (*European Hygienic Engineering & Design Group*).
- ☑ **FSDS** (*Food Storage and Distribution Federation*), **FDF** (*Food and Drink Federation*), **CFA** (*Chilled Food Association*), **BFFF** (*British Frozen Food Federation*), **IOR** (*Institute of Refrigeration*) in the UK.

As a result of the above-mentioned endeavours, survey information and the relevant Call for CryoHub Champions (see Section 3.1.4) were published worldwide by various international organisations and networks, specialised periodicals, professional magazines and mass media, some of which are mentioned in Figure 2.

Figure 2. Some organisations and media, which intensively promoted the CryoHub Survey and Call for Champions.

Simultaneously, the WP2 leader K. Fikiin presented CryoHub, along with the relevant survey and Call for Champions, at several conference events, e.g.:

Fikiin K. (2016). CRYOHUB – Cryogenic energy storage at refrigerated food warehouses to enhance the sustainability of cold chain and power supply. *Proceedings of the 6th International Conference on Cold Chain Management and Temperature Controlled Logistics,* Bonn (Germany), 6-7 June 2016, http://www.ccm.ytally.com

Fikiin K. (2016). Cryogenic Energy Storage for Renewable Food Refrigeration and Power Supply. Keynote Presentation, *30th EFFoST International Conference,* Vienna (Austria), 28-30 November 2016

In addition, the following CryoHub-related scientific publication has recently appeared:

Fikiin K., Stankov B., Evans J., Maidment G., Foster A., Brown T., Radcliffe J., Youbi-Idrissi M., Alford A., Varga L., Alvarez G., Ivanov I. Evg., Bond C., Colombo I., Garcia-Naveda G., Ivanov I. Evg., Hattori K., Umeki D., Bojkov Ts., Kaloyanov N. (2016). Refrigerated warehouses as intelligent hubs to integrate renewable energy in industrial food refrigeration and to enhance power grid sustainability. *Trends in Food Science & Technology,* http://dx.doi.org/10.1016/j.tifs.2016.11.011

The complete bibliographical data of the article will be available soon and it will be sent to a depository to meet the Open Access requirements of Horizon 2020.

The CryoHub project, survey and Call for Champions were also presented at IIR sponsored and co-sponsored conferences around the globe (Figure 3), alongside the IIR newsletters, web-publications and e-mailings to IIR members of different categories.

Figure 3. CryoHub presented at IIR conferences worldwide.

3.1.4. CryoHub Champions and their certification

To maximise the expected response to the CryoHub mapping survey, an Awarding System was designed in the following way. All organisations properly completing the survey obtain the status of *'Bronze CryoHub Champions'.* Those wishing and endorsed to host a case study visit on site are named *'Silver CryoHub Champions'*. Finally, the warehousing company willing and approved to host the Demonstration plant is prominently acknowledged as the *'Gold CryoHub Champion'*.

Warehouse owners and operators wishing to:

- boost their company sustainability credentials;
- gain free publicity and a green image across Europe;
- be recognised as an environmental pioneer in a high-profile EU project;
- tune into cutting-edge energy storage research;
- identify methods for energy saving and grid feed-in;

were kindly invited to apply ASAP for the status of a *'CryoHub Champion'* by completing the mapping survey. A special Call for CryoHub champions was prepared and disseminated worldwide for that purpose (Figure 4).

To Whom It May Concern:

Dear Ladies and Gentlemen,

Subject: Call for cooperation with the EU's CryoHub project and applications for *'CryoHub Champions'*

As you are known to be one of the foremost professional organisations dealing with refrigeration and food cold chain across Europe and worldwide, we would like to bring to your attention an exciting pan-European research and innovation action. This should be of paramount interest to your member companies as it might dramatically change the future of our metier. Hence, we will be extremely grateful if you familiarise your members with the information detailed below.

The CryoHub innovation project (www.cryohub.eu) investigates and extends the potential of large-scale Cryogenic Energy Storage (CES) and applies the stored energy for both cooling and power generation. By employing Renewable Energy Sources (RES) to liquefy and store cryogens, CryoHub balances the power grid, while meeting the cooling demand of a refrigerated food warehouse and recovering the waste heat from its equipment and components.

As you know, the intermittent supply is a major obstacle to the RES power market. Renewables are fickle sources, prone to overproducing when demand is low whilst failing to meet requirements when demand peaks. As Europe is about to generate 20% of its energy demand from RES by 2020, the adequate RES integration and renewable energy storage throughout the entire food cold chain poses continent-wide challenges.

The Cryogenic Energy Storage (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, the cryogen serves for grid energy storage and is boiled, when needed, to drive a power generator and to restore electricity to the grid. To date, CES applications have been rather limited because of the poor efficiency due to unrecovered energy losses.

The CryoHub project is therefore designed to maximise the CES efficiency by recovering energy from cooling and heating through a RES-driven cycle of cryogen liquefaction, storage, distribution, efficient use and power regeneration. Refrigerated warehouses or factories 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 advance and demonstrate the CES benefits.

CryoHub is an intelligent technology capable of converting a conventional refrigerated warehouse or food factory from a simple power consumer to an interactive energy hub, thus providing substantial economic and environmental benefits for both the food refrigeration and energy sectors. **CryoHub has nothing to do with the long-lasting competition between *'mechanical'* and *'cryogenic'* refrigeration in the food preservation sector.** The project brings together the advantages of both principles and overcomes most of the existing bottlenecks at one go, thereby broadening the market prospects for sustainable energy technologies across Europe.

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This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 691761.

More information: www.cryohub.eu

Coordinator: Prof. Judith Evans (j.a.evans@lsbu.ac.uk)

The CryoHub project consortium, in coordination with the European Commission, is privileged to invite you hereby to become part of one of the most fascinating innovation actions in the food refrigeration sector over the recent decades. Join us ASAP and apply for the status of a *'CryoHub Champion'* company by completing the 5-minute CryoHub Mapping Survey (www.surveymonkey.co.uk/r/cryohub) and expressing your potential desire to host free Case Studies or the CryoHub Demonstration Plant.

If you wish to:

- boost your company sustainability credentials;
- gain free publicity and a green image across Europe;
- be recognised as an environmental pioneer in a high-profile EU project;
- tune into cutting-edge energy storage research;
- identify methods for energy saving and grid feed-in;

does not miss to apply ASAP for the status of a *'CryoHub Champion'*, as detailed in www.surveymonkey.co.uk/r/cryohub

Those who properly complete the survey will be recognised as ***'Bronze'* CryoHub Champions.** Applicants for Case Study and Demo Plant hosts will further be contacted to investigate their preferences and local conditions on site. Selected hosts for Case Studies and the Demo Plant will be distinguished as ***'Silver'* and *'Gold'* CryoHub Champions,** respectively. All CryoHub Champions will be rewarded with a Certificate and publication of their company logo in a dedicated section of the CryoHub website (www.cryohub.eu).

Very truly yours,

As Prof. Kostadin FIKIIN
Work Package Leader
Technical University of Sofia (Bulgaria)

Prof. Judith EVANS
Project Coordinator
London South Bank University (UK)

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 691761.

More information: www.cryohub.eu

Coordinator: Prof. Judith Evans (j.a.evans@lsbu.ac.uk)

Figure 4. Call for CryoHub Champions.

Thus, the CryoHub project consortium, in coordination with the European Commission, was privileged to invite cold chain actors to become part of one of the most fascinating innovation actions in the food refrigeration sector over the recent decades. All CryoHub Champions are rewarded with a Certificate and publication of their company logo in a dedicated section of the CryoHub website (www.cryohub.eu), as indicated in Figure 5.

Figure 5. Certificate of a CryoHub Champion.

3.1.5. Response to the survey

In spite of all aforementioned efforts, the survey received a scarce public response so far (Figure 6). This might be explained by the conservatism in the sector and the reluctance of warehouse operators to share their energy data. On the other hand, a much longer duration of the survey use is certainly needed to obtain more representative and comprehensive results.

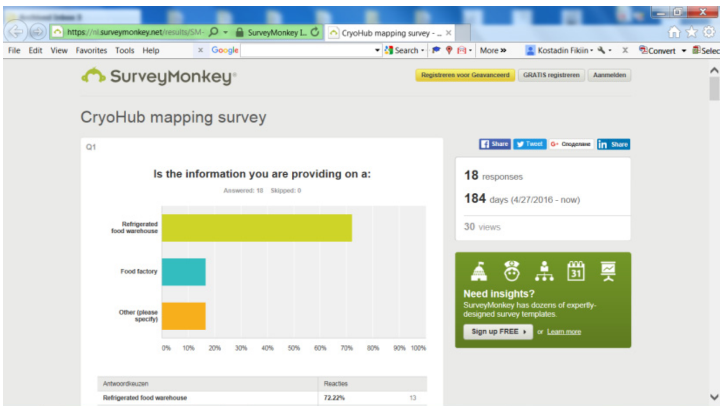


Figure 6. Response to the CryoHub mapping survey.

3.2. Snowballing and data elaboration

3.2.1. Estimating the energy use of refrigerated food facilities

It was clear that the lack of survey data would not permit to provide a comprehensive map of energy consumption throughout Europe within the planned 10-month period. Another approach was therefore considered and employed, based on capacity data. This requires determining the volume of the refrigerated warehouse and then using a specific energy consumption to estimate the energy spent. A special Excel spreadsheet for data collection was elaborated for that purpose (Figure 7).

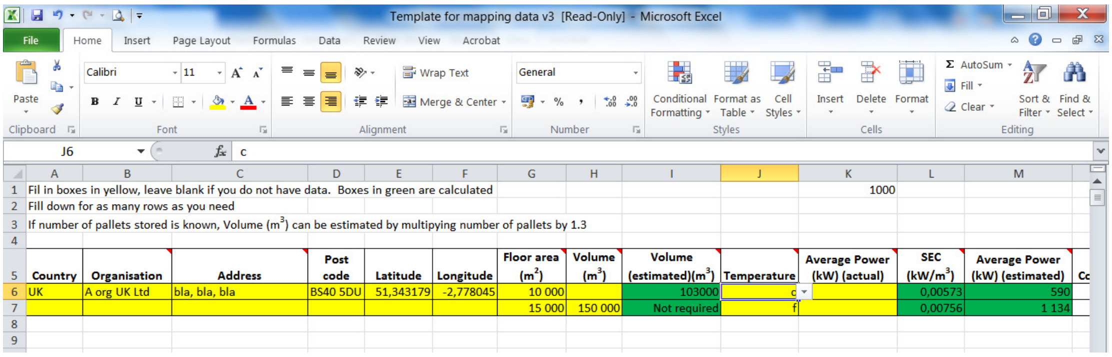


Figure 7. Excel spreadsheet for power consumption data collection.

The specific energy consumption was obtained from our previous work:

Evans J., Foster A.M., Huet J.-M., Reinholdt L., Fikiin K., Zilio C., Houska M., Landfeld A., Bond C., Scheurs M. and Van Sambeck T. (2015). Specific energy consumption values for various refrigerated food cold stores. *Proceedings of the 24th IIR International Congress of Refrigeration,* Yokohama (Japan), 16-22 August 2015, ID: 481, DOI: 10.13140/RG.2.1.2977.8400

The capacity information used contained the volume of the warehouse or, alternatively, mass of products or pallets that could be stored, and floor area. A correlation of mass and volume was derived from 19 German refrigerated warehouses, which contained both metrics. The correlation showed that 1 tonne was equivalent to 1 m^3. For the same 19 warehouses, a correlation of 3.3 m^3 per pallet was given. If only floor area was known, a nominal height was chosen to provide a volume. The nominal height chosen was 10.3 m which was an average of UK data. Where there was no data, volume was estimated by using Google Maps to find the refrigerated warehouse and then using the Google measurement tool to ascertain the floor area. Google Streetview could then be used to ascertain height by comparing the height of the store with items of known height, e.g. pedestrian doors and refrigerated containers.

The volume of each refrigerated warehouse was multiplied by its respective specific energy consumption to produce the estimated warehouse power usage.

3.2.2. Sources of data for refrigerated facility locations and capacities

Existence of reliable information for warehouse locations and capacities (in terms of m^2, m^3, tonnes or pallet number) is vital to run the above-mentioned alternative energy estimation method. Different databases found and used for that purpose can be summarised as follows:

- Printed editions of the GCCA International Cold Chain Directory, GCCA Directory of Refrigerated Warehouse and Distribution Centres, ECSLA Directory of European Cold Stores, etc. (Figure 8).

Figure 8. Printed publications of GCCA (IARW & WFLO) and ECSLA as a source of refrigerated warehouse capacity and localisation data.

- On-line Global Cold Chain Directory of GCCA: www.gcca.org/gcca-directory (Figure 9).

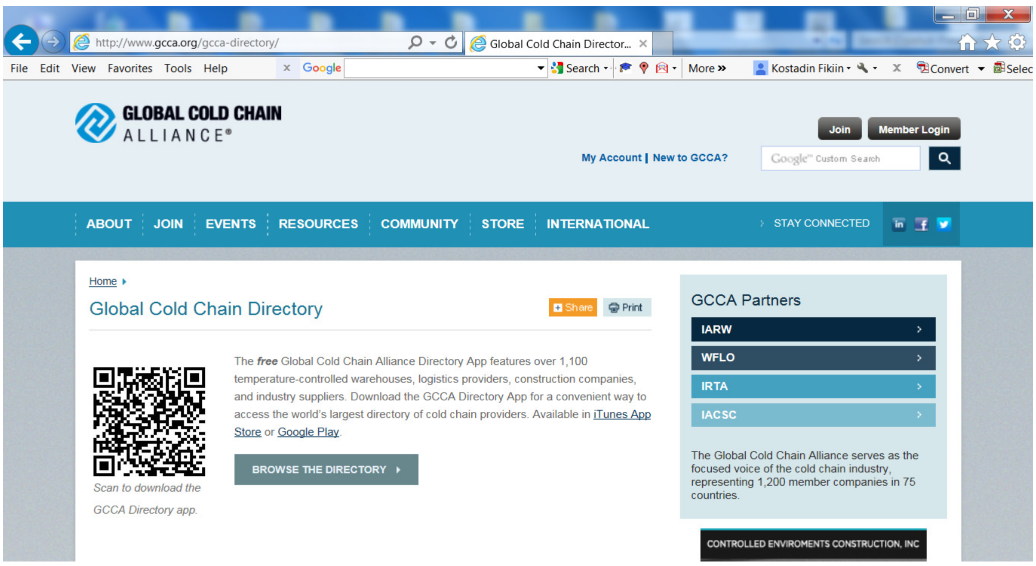


Figure 9. Web-based GCCA Global Cold Chain Directory

- Euro-pages on the Internet (Business Directory).
- Data of UK Environment Agency (through the freedom of information act).
- Database of French Ministry of Environment (containing both capacity and energy consumption figures).
- DG SANTE website linked to the sites of national food safety authorities, providing information for refrigerated warehouses and food factories permitted to operate in an EU level.
- National cold chain associations.

3.2.3. Waste heat

Unless the refrigerated warehouses are attached to a food factory or a facility which uses a large amount of heat, then the majority of waste heat comes from the refrigeration condensers. Unless the warehouse makes use of waste heat recovery, then the condenser heat will be lost to the ambient. It would be possible to capture this waste heat and use it to further heat the cryogen above ambient temperature, however, the temperature of the waste heat is likely to be approximately 35 °C. For high round trip efficiencies of the energy storage, temperatures in the order of 60 to 600 °C might be efficient (the higher the better), which might eventually be recovered from the air liquefaction compressors. Hence, it is unlikely to use waste heat from the warehouse refrigeration system.

3.2.4. Energy use over time

Figure 10 represents the monthly average energy use in a supermarket warehouse distribution centre over the period of one year. The amount of energy does not vary much deal due to seasonal differences. The maximum monthly mean energy was 953 kW, with a minimum energy consumption in February of 810 kW and a maximum in July of 1100 W. The energy is generally higher in the summer and lower in the winter. However, it is higher than expected between November and January, possibly due to Christmas and New Year shopping.

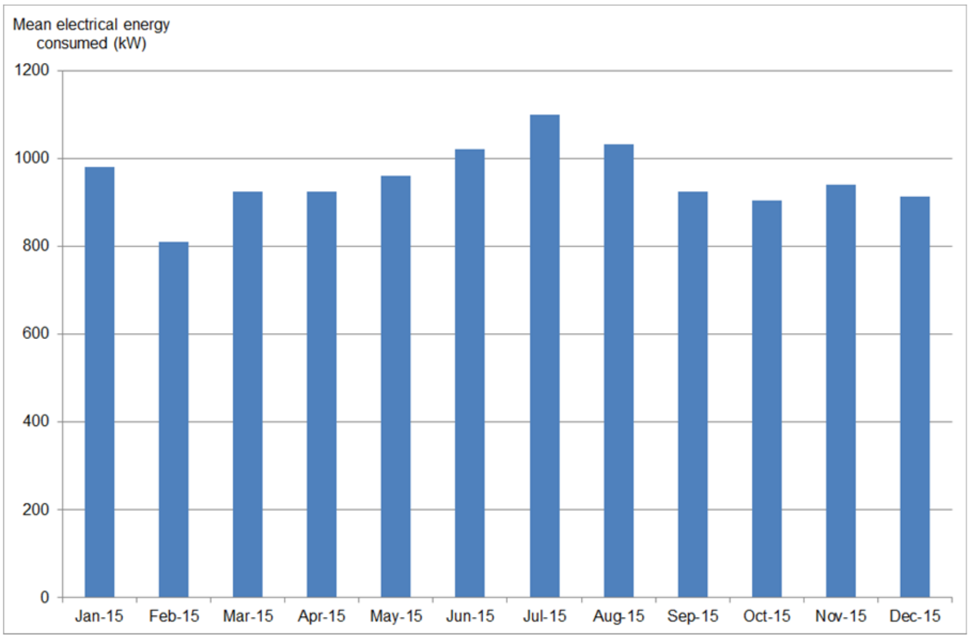


Figure 10. Energy use in a supermarket warehouse distribution centre over the period of one year, averaged over a month (Source: LSBU).

Figure 11 shows the energy use in a supermarket warehouse distribution centre during August, averaged every half hour. The energy varies a great deal due to daily fluctuations, with a mean of 1068 kW, maximum of 1962 kW and a minimum of 622 kW.

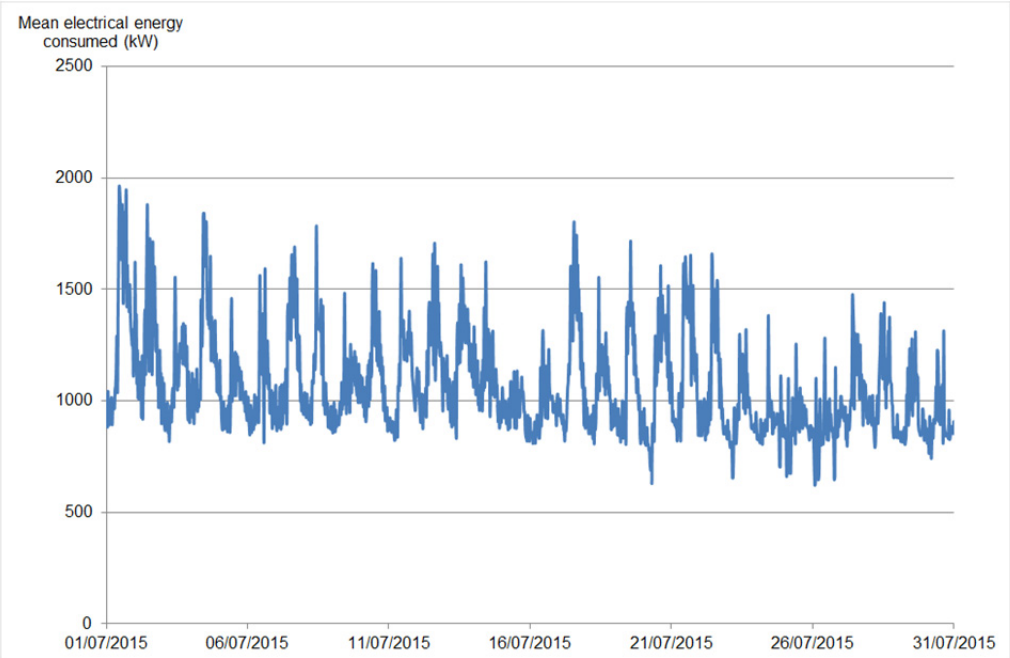


Figure 11. Energy use in a supermarket warehouse distribution centre during August, averaged every half hour (Source: LSBU).

A year later, the warehouse distribution centre had installed solar panels. Figure 12 illustrates the energy consumption of the facility over the same period (July) in the next year. Mean energy has dropped by 273 kW to 795 kW. The minimum energy is now zero, which shows there are some periods when the solar panels are providing all the energy for the facility.

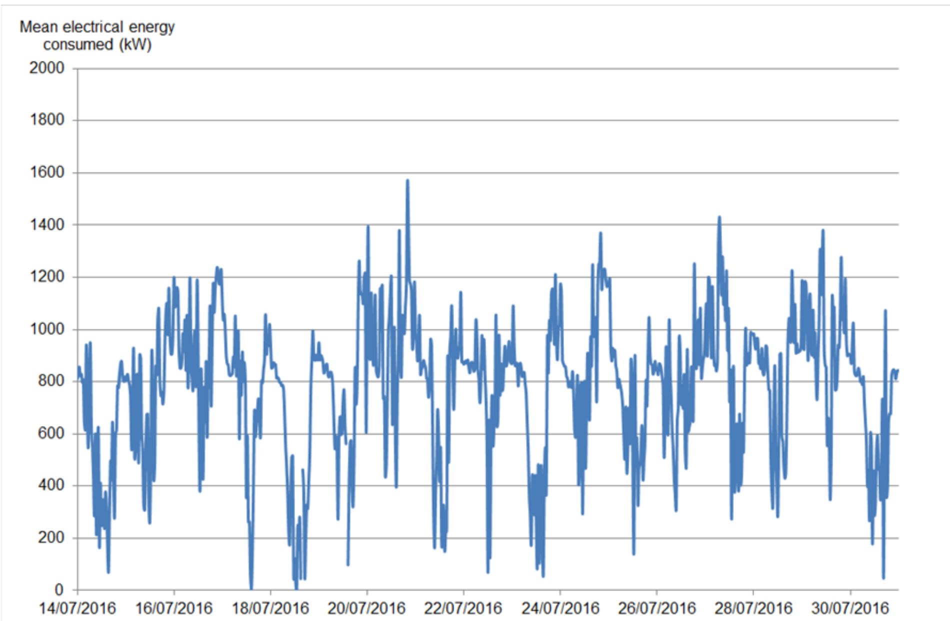


Figure 12. Energy use in a supermarket warehouse distribution centre during August, averaged every half hour with solar panels fitted (Source: LSBU).

Figure 13 depicts the electrical energy consumed by the facility, and generated by the solar panels in a day in July. The difference between these two values is the net electricity imported from the grid to run the facility. The facility has a base load of about 1000 kW which increases during the day to about 2000 kW. This is probably due to the facility's overuse during the day and the warmer ambient temperatures. The solar panels generate energy between approximately 07:00 h and 21:00 h, peaking between 14:00 and 16:00 h, which leads to a drop in the energy the facility imports from the grid during the middle of the day to zero at about 14:00 h.

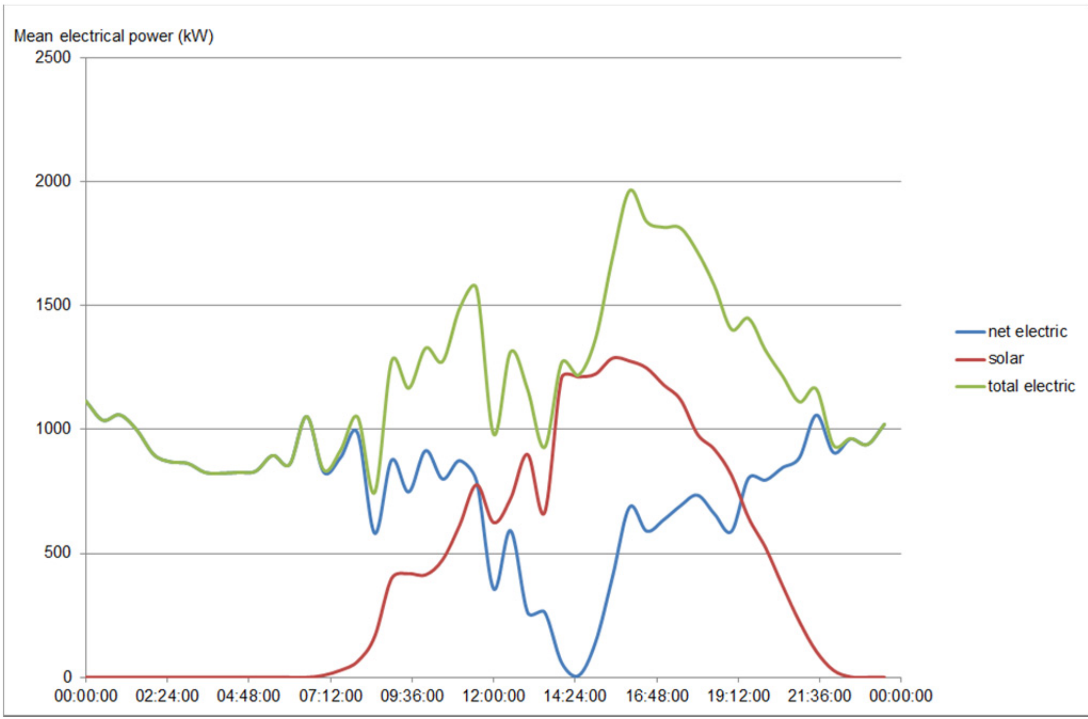


Figure 13. Electrical energy consumed by the facility, and generated by solar panels in a day in July (Source: LSBU).

3.3. Elaboration of the CryoHub energy consumption maps

After completing the data set with warehouse locations (latitudes and longitudes) and power consumption information, the next logical step was to produce the desired energy maps. ArcGis was chosen as mapping software because of its following capabilities:

- ☑ Easy manipulation of data (e.g. by converting coordinate systems).
- ☑ Facilitated data analysis (e.g. when determining the nearest warehouse distance to RES).
- ☑ Opportunity to create bespoke mapped outputs (from simple mapped outputs to processed ones).
- ☑ Popularity of the software (given ESRI is the leading producer of GIS software).
- ☑ Readili available to the CryoHub consortium (as CRAN has long successful experience with ArcGis).

Maps of refrigerated food facilities were produced for EU28, as well as for the following country groups: (i) Benelux (Belgium, the Netherlands and Luxemburg); (ii) Central and Eastern Europe (Bulgaria, Croatia, Czech Republic, Hungary, Poland, Romania, Slovakia and Slovenia); (iii) Germany and Austria; (iv) Mediterranean countries (Cyprus, France, Greece, Italy, Malta, Spain and Portugal); (v) Nordic and Baltic EU countries (Denmark, Estonia, Finland, Latvia, Lithuania and Sweden); (vi) United Kingdom and Ireland. The gathered database was filtered so as the maps elaborated indicate only large refrigerated facilities spending over 500 kW of electrical power for refrigeration purposes.

4. Results and discussion

4.1. European Union

While a total of 1049 refrigerated food warehouses were explored throughout EU, some 503 of them had a power consumption exceeding 500 kW as shown in the statistical overview, presented in Table 1.

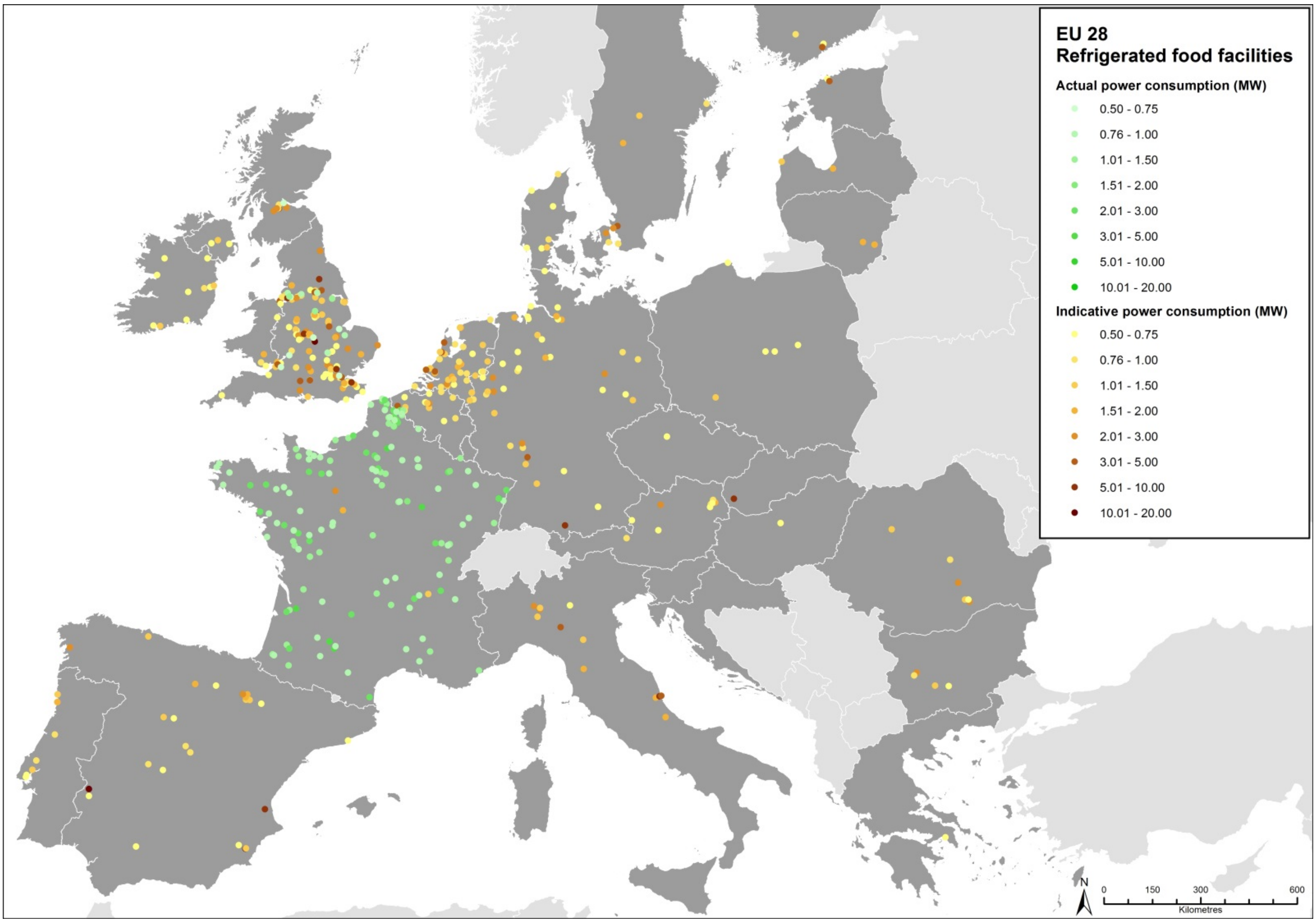


Figure 14. Map of large refrigerated food warehouses (> 0,5 MW) across EU 28.

These 503 highly energy intensive warehouses were placed on the European map, as indicated in Figure 14. It is easy to notice that the highest concentration of such large refrigeration facilities exists along both sides of the English Channel (e.g. in Benelux, Sothern England, Northern France and Northern Germany). This coincides very logically with the highest population density in Europe approximately in the same regions.

Table 1. Summary of the explored refrigerated food facilities across Europe.

Country	Number of all facilities explored	Indicative power consumed by all facilities (MW)	Actual Power consumed by all facilities (MW)	Number of large facilities* (MW)	Indicative power consumed by large facilities* (MW)	Actual power consumed by large facilities* (MW)
Austria	20	13,78		10	10,43	
Belgium	22	17,91	0,49	14	15,72	
Bulgaria	14	6,47		4	4,70	
Cyprus	5	1,19		0	0,00	
Czech Republic	8	2,45		2	1,32	
Denmark	28	17,34		12	12,84	
Estonia	4	4,32		2	3,84	
Finland	12	6,98		3	4,96	
France	146	14,94	214,03	146	6,66	214,03
Germany	142	75,01		44	53,76	
Greece	11	2,62		1	0,53	
Hungary	11	2,16		1	0,59	
Ireland	27	12,24		11	8,32	
Italy	16	29,60		12	28,64	
Latvia	6	3,83		2	2,91	
Lithuania	7	5,41		3	4,55	
the Netherlands	143	90,39		45	70,54	
Poland	9	4,71		5	3,63	
Portugal	19	10,43		7	7,06	
Romania	11	10,31		6	8,81	
Slovakia	5	6,28		1	5,08	
Slovenia	5	1,02		0	0,00	
Spain	31	59,05		24	56,33	
Sweden	20	13,35		6	10,03	
United Kingdom	327	292,97	13,66	142	232,03	12,53
Grand Total	**1049**	**704,76**	**228,18**	**503**	**553,27**	**226,56**

* with a power consumption over 0.5 MW

As illustrated in Table 1, this study covered comprehensively EU 28, with a little exception for Croatia, Malta, Luxemburg, where less attention was paid and no facilities were taken into account. While the first of these countries is the newest EU member, no indications were found for existence of large facilities in the second two states.

The indicative power usage figures in Table 1 are determined by means of capacity search and further use of specific energy consumptions (as previously detailed in Section 3.2.1). The actual figures for Belgium, France and UK were obtained by using either the web-based CryoHub survey or figures provided by national authorities (French Ministry of Environment and UK Environment Agency).

4.2. Groups of countries

A number of EU countries' groups have been identified and classified (based on their geographical location; climatic similarities; traditions; economic, administrative and cultural interlinks), as follows: **(i)** Benelux (Belgium, the Netherlands and Luxemburg); **(ii)** Central and Eastern Europe (Bulgaria, Croatia, Czech Republic, Hungary, Poland, Romania, Slovakia and Slovenia); **(iii)** Germany and Austria; **(iv)** Mediterranean countries (Cyprus, France, Greece, Italy, Malta, Spain and Portugal); **(v)** Nordic and Baltic countries (Denmark, Estonia, Finland, Latvia, Lithuania and Sweden), and **(vi)** UK and Ireland. These groups of countries are hereafter highlighted in more details.

4.2.1. Benelux

Benelux is a politico-economic union possessing numerous large refrigerated food facilities, as depicted in Figure 15. In particular, some 59 warehouses consuming over 500 kW of power were found on the territory of Belgium and the Netherlands. These warehouses spend some 11 % of the overall power consumed by such large facilities Europe-wide.

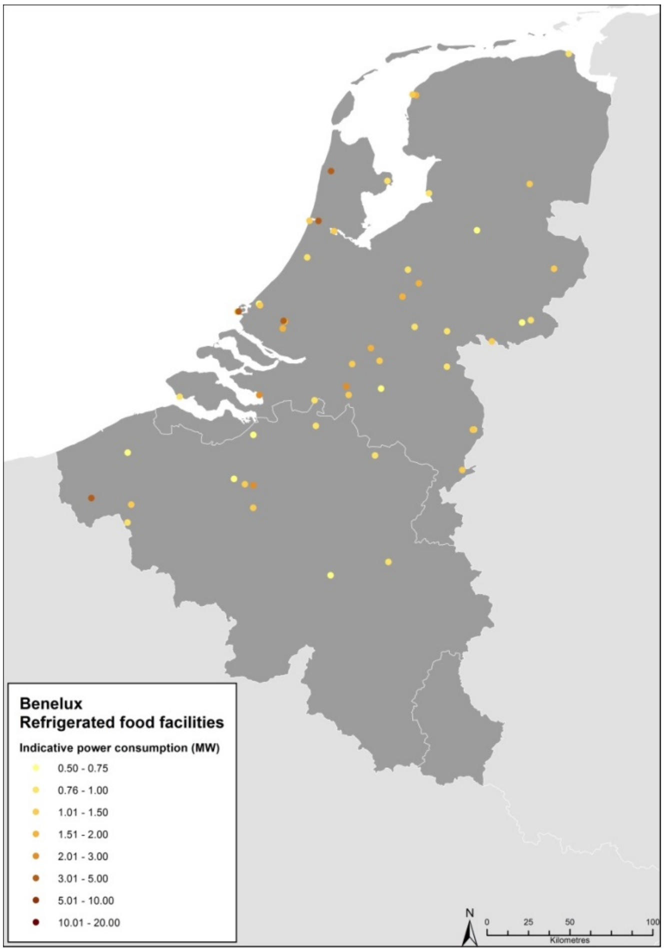


Figure 15. Map of large refrigerated food warehouses (> 0,5 MW) in Benelux.

If all 165 facilities found in the region are taken into account, then the energy consumption share of Benelux will account for some 12 % of the overall power expenditure by all warehouses explored in EU 28.

4.2.2. Central and Eastern Europe

This region comprises mainly countries, which joined the EU in 2004 and 2007. Although less large warehouses than in Western Europe can be identified, the cold chain sector is rapidly growing and the market is very dynamic. Energy intensive warehouses, spending over 500 kW of electrical power (Figure 16), belong, in the most cases, to the logistics and distribution centres of multinational retailers and hypermarket operators.

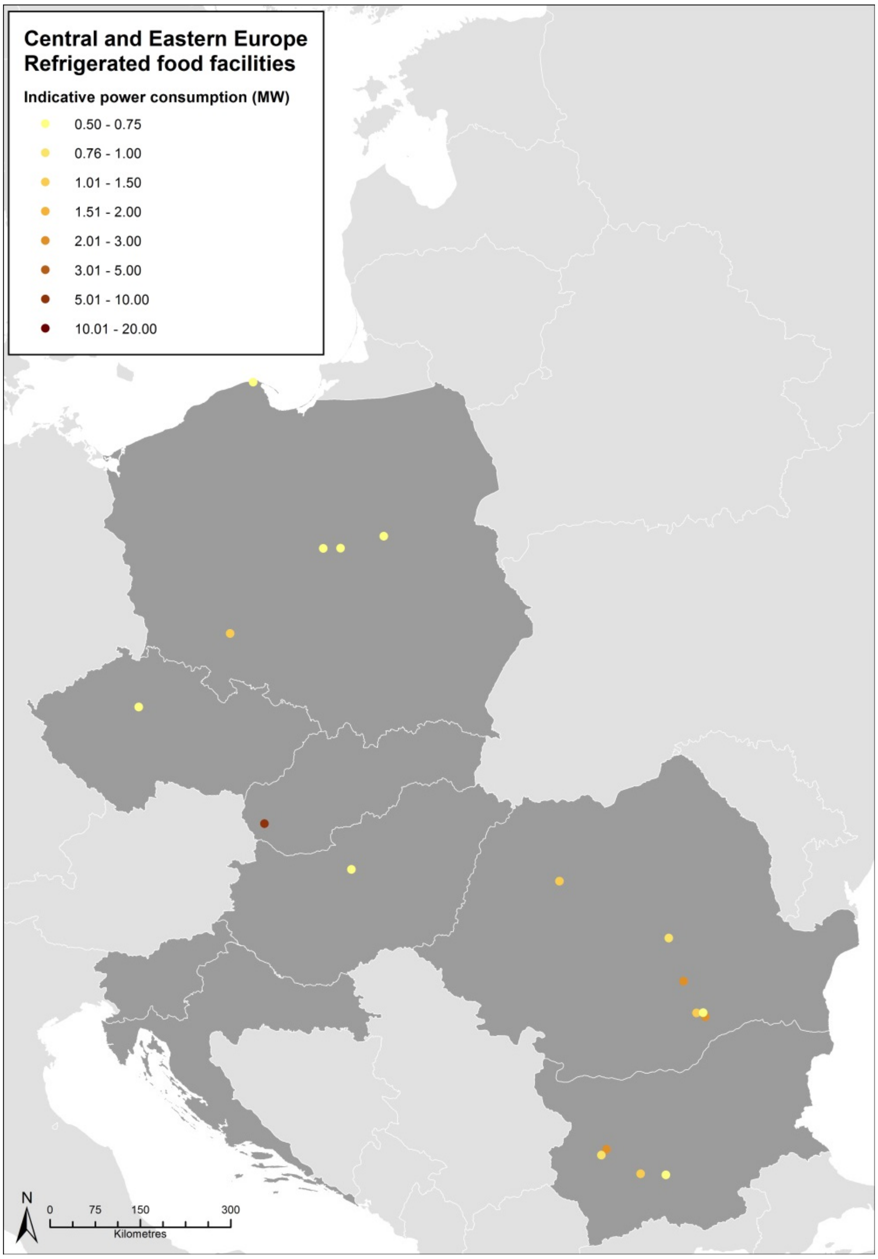


Figure 16. Map of large refrigerated food warehouses (> 0,5 MW) in Central and Eastern Europe.

Some 19 large warehouses (> 0,5 MW) were discovered in the region, consuming 3 % of the power spent for running such warehouses in the entire of Europe. Overall, 63 more significant warehouses were identified, which have a share of nearly 4 % of the electrical power consumed Europe-wide by all warehouses explored.

4.2.3. Germany and Austria

This group of countries is traditionally well equipped with refrigerated food facilities of diverse nature. Some 55 large refrigerated warehouses spending over 500 kW were found out (Figure 17), which constitute about 8 % of the power expenditure by such warehouses across the continent.

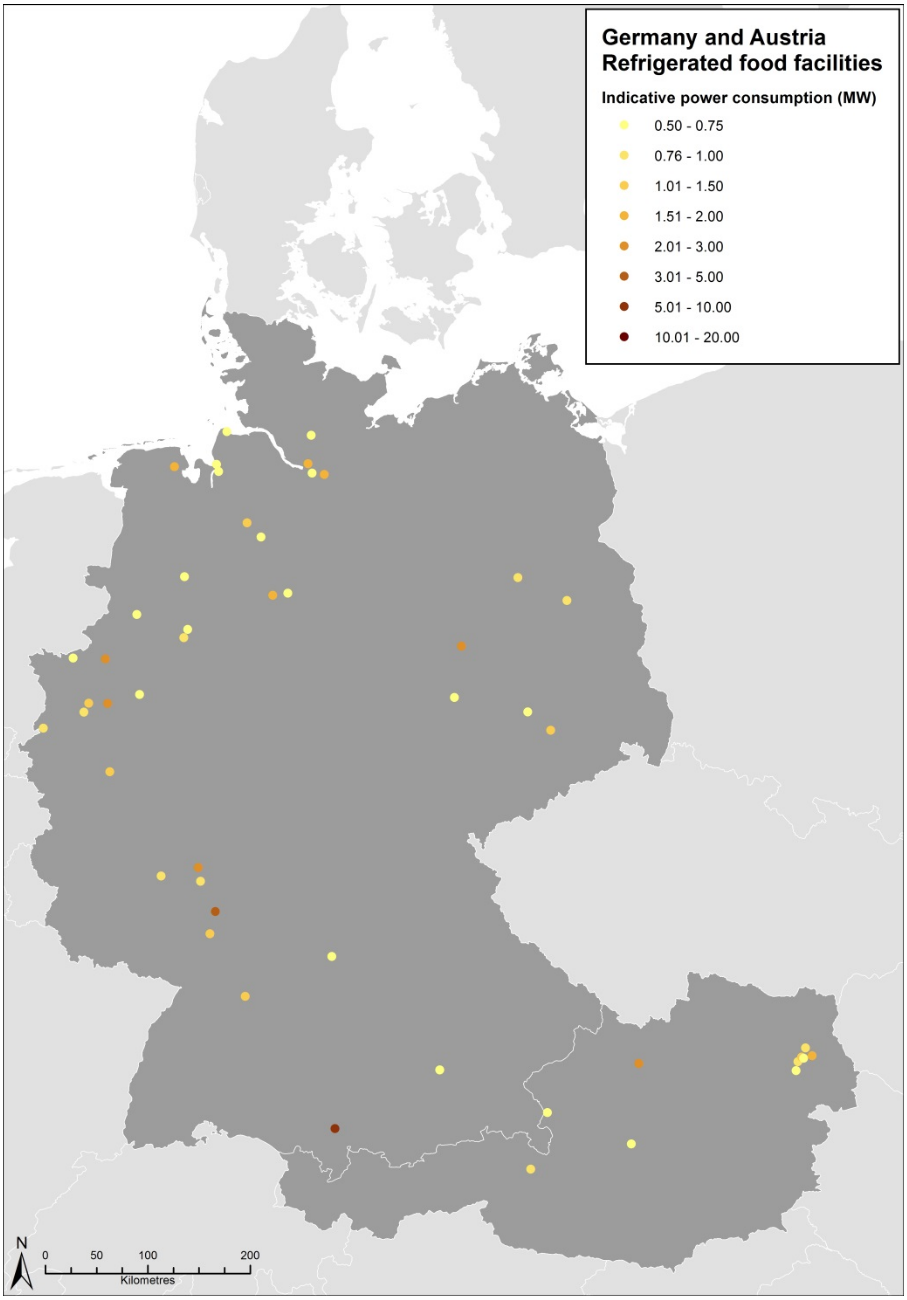


Figure 17. Map of large refrigerated food warehouses (> 0,5 MW) in Germany and Austria.

When taking into account all 162 warehouses identified, it appears that this countries' group accounts for nearly 10 % of the overall electrical energy consumed by all EU refrigerated food warehouses participating in this data collection exercise.

4.2.4. *Mediterranean countries*

This is a rather large countries' group which includes Europe's top producers of agricultural and food commodity. Consequently, most of the Mediterranean countries have a well-developed food cold chain, with an impressive number of refrigerated food facilities of any size and purpose.

The discovered large refrigerated storage warehouses, exceeding the power consumption of 500 kW (Figure 18), amounted to 190, which represent about 42 % of the electrical power spent by such facilities in Europe.

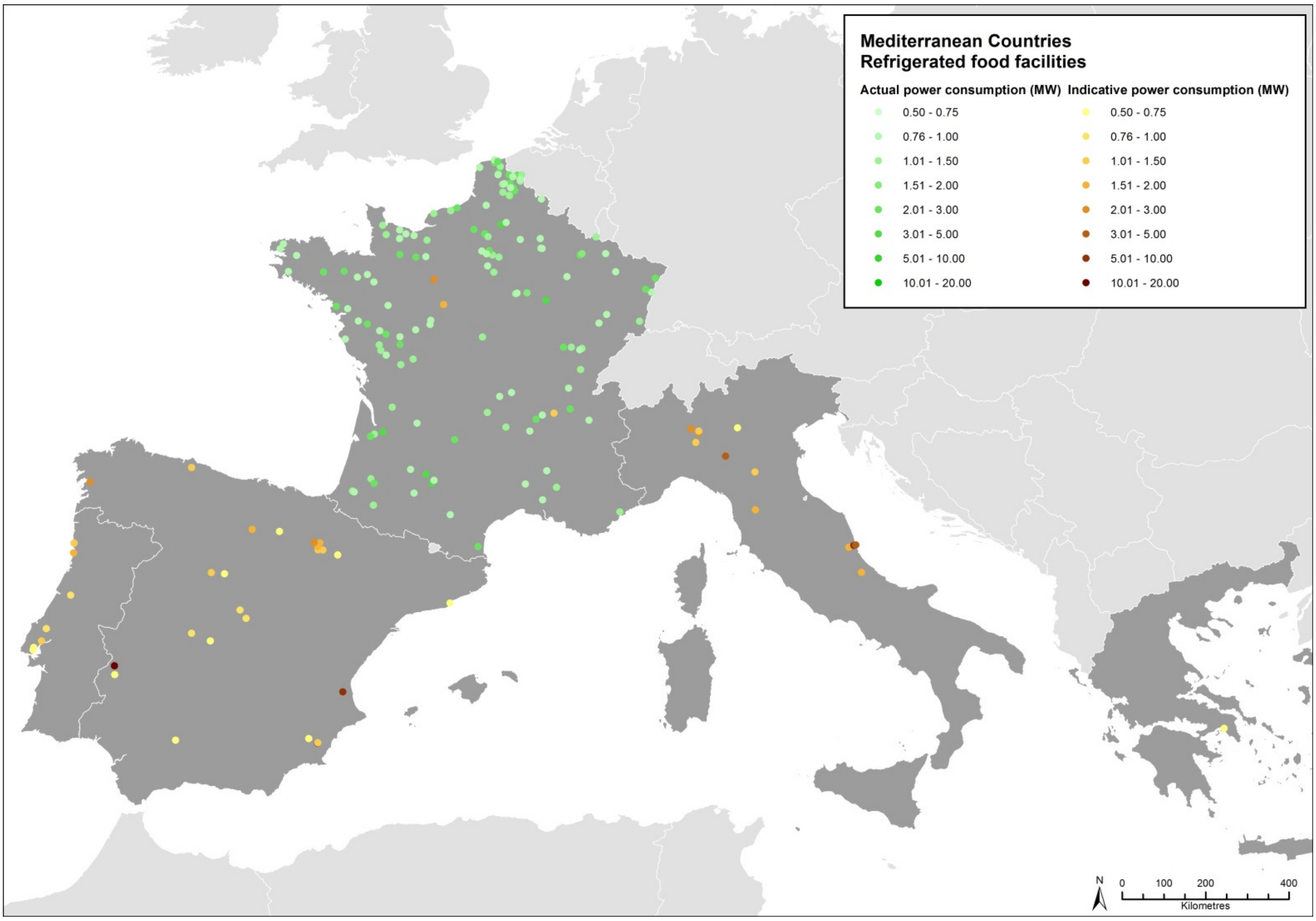


Figure 18. Map of large refrigerated food warehouses (> 0,5 MW) in the Mediterranean countries.

As a whole, all warehouses, identified in the Mediterranean region, amount to 228, which are responsible for approx. 37 % of the electrical power spent Europe-wide by all facilities taking part of the data gathering exploration.

The thoroughness and high accuracy of the data collected for France merit special attention. Due to the kind assistance of the French Ministry of Environment, approached by IRST and agreeing to share power consumption figures for hundreds of warehouses throughout France, a complete database was built, which contains actually measured values, rather than recalculated ones.

4.2.5. Nordic and Baltic countries

The group comprises the three Nordic EU member countries, along with the three Baltic states which joined EU in 2004. It is obvious that the concentration of warehouses depends on the population density and the climatic conditions. Most of the large refrigerated food facilities (consuming over 500 kW of electrical power) are located in the Southern part of this geographical region (Figure 19), which is more populated. On the contrary, no such warehouses can be found in the Northern areas with less population and cold climate capable of providing natural cooling for perishable food commodities.

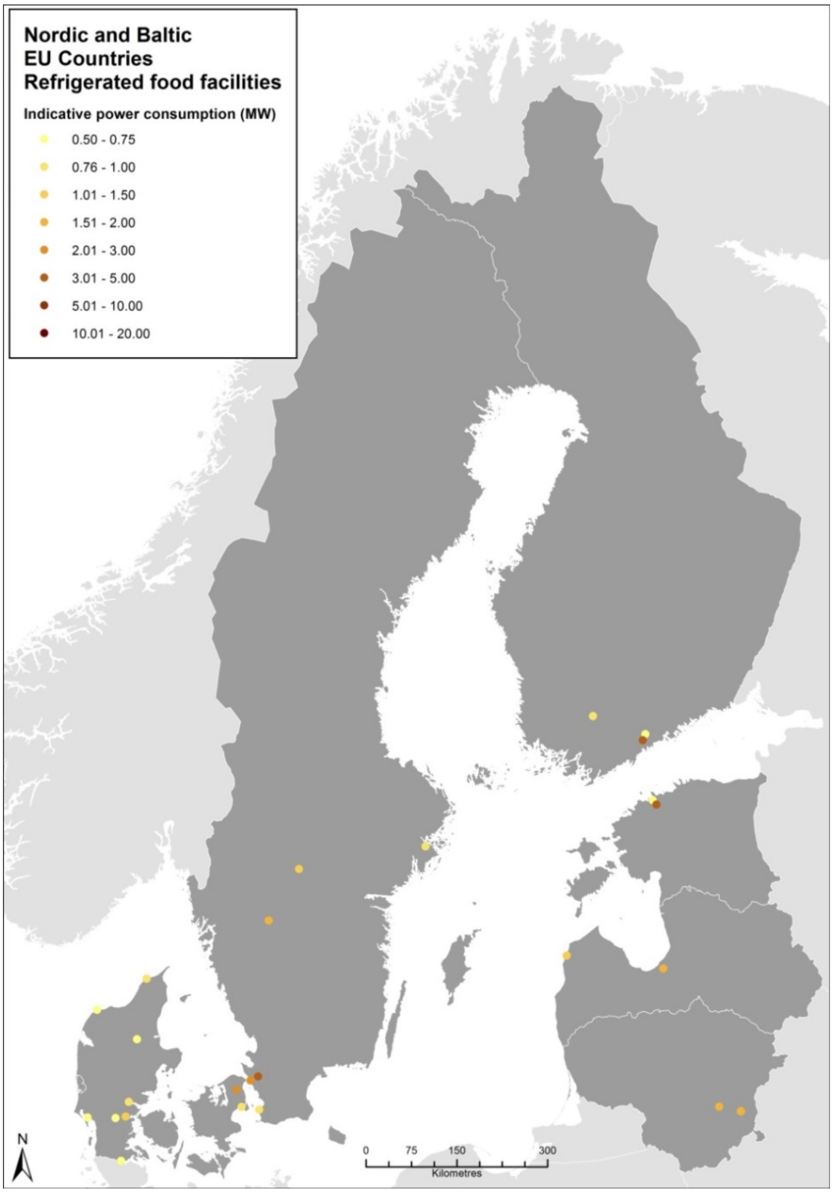


Figure 19. Map of large refrigerated food warehouses (> 0,5 MW) in the Nordic and Baltic countries.

Some 28 large refrigerated warehouses (over 0,5 MW) were identified in this region, responsible for 5 % of the power spent by such facilities in EU 28. Overall, 77 warehouses were explored, whose electrical energy expenditure slightly exceed 5 % of the consumption of all facilities investigated Europe-wide.

4.2.6. United Kingdom and Ireland

Traditionally, this geographical region is rich of refrigerated food facilities. It is easy to notice that the large refrigerated warehouses (spending over 500 kW of power) are mainly concentrated in the industrial and highly populated regions of Southern and Central England, along with the territory around Edinburg in Scotland, with a lesser but perceptive presence in Northern Ireland and the Irish Republic (Figure 20).

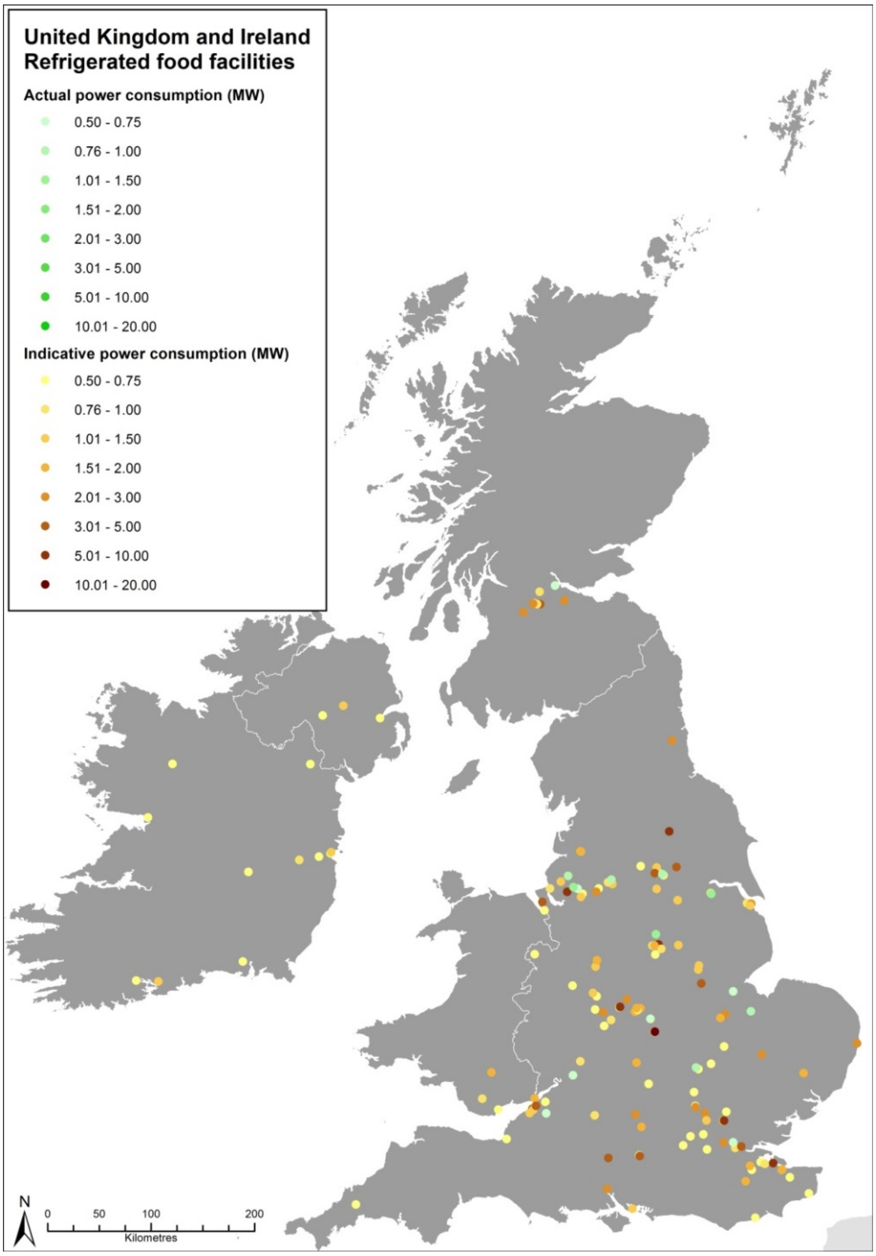


Figure 20. Map of large refrigerated food warehouses (> 0,5 MW) in the UK and Ireland.

The CryoHub consortium explored some 354 refrigerated warehouses in the UK and Eire (spending nearly 33 % of the associated power in the whole of Europe) to identify 153 large warehouses (>0,5 MW) accounting for approx. 31 % of the electricity consumed by all such facilities throughout the continent.

4.3. Comparison between the CyoHub and GCCA / ICE-E surveys

To ascertain whether the CryoHub mapping survey adequately represents the amount of cold storage capacities and resulting energy expenditure in Europe, a comparison was made of the CryoHub results with those of the 2010 IARW Global Cold Storage Capacity Report (by Victoria Salin, Texas A&M University, for the International Association of Refrigerated Warehouses). This document provides an update on global cold storage capacity, using information collected from international offices of GCCA (Global Cold Chain Alliance). The primary data source was a survey administered in fall 2010. A newer version named 2016 GCCA Global Cold Storage Capacity Report is also available, along with the associated web-based GCCA Global Cold Chain Directory (as outlined in Section 3.2). The capacities of explored refrigerated warehouses are shown in Table 2.

Table 2. Refrigerated storage warehouse space in millions of cubic meters.

Country	GCCA	CryoHub	Difference (CryoHub – GCCA)	Ratio (Cryohub / GCCA) (%)
Austria	0.8	1.9	1.1	238%
Belgium	2	2.4	0.4	120%
Bulgaria		0.9		
Czech Republic		0.3		
Denmark	1.9	2.3	0.4	121%
Finland	1.8	0.9	–0.9	50%
France	8.5	3.2	–5.3	38%
Germany	21.8	10.0	–11.8	46%
Great Britain	5.6	39.4	33.8	704%
Greece	0.9	0.4	–0.5	44%
Ireland	1.7	1.6	–0.1	94%
Italy	3.5	6.3	2.8	180%
the Netherlands	12.6	12.2	–0.4	97%
Poland	0.3	0.8	0.5	267%
Portugal	0.8	1.6	0.8	200%
Spain	8.2	8.3	0.1	101%
Sweden	0.9	1.8	0.9	200%
Total	**71.3**	**94.3**	**23**	**132%**

The above figures indicate that the CryoHub project found more warehouse volumes than the GCCA report. To a large extent this is due to the substantial warehouse capacity discovered in the UK, as compared with the limited amount presented by GCCA. CryoHub has found more warehouse space than GCCA for 12 out of the 17 countries. For two of these countries GCCA had no data at all. The comparison also reveals that the CryoHub database can further be improved by paying more attention to some of the countries, such as France and Germany, which are expected to have more cold storage capacities than were actually identified by the CryoHub data gathering exercise.

Another important data survey, CryoHub is to be compared with, is ICE-E[1]. The main features and capabilities of the three datasets considered are summarised in brief in Table 3.

Table 3. Functionality of different international surveys of refrigerated warehouses.

Survey	Capacity Data	Location Data	Energy data	Mapping
GCCA	YES	YES	NO	NO
ICE-E	YES	PARTLY	YES (mostly actual)	NO
CryoHub	YES	YES	YES (mostly indicative)	YES

Obviously, CryoHub represents a substantial advancement, as compared with GCCA and ICE-E, because this is the only international survey of refrigerated food warehouses which brings together capacity, geographical and energy information, including Europe-wide mapping suitable for further analysis and strategy planning in the food refrigeration sector. Let us remind, however, that GCCA affords a global survey, which does not focus specifically on Europe.

5. Conclusions and recommendation

The present CryoHub deliverable D2.1 provided a comparatively comprehensive database about the large refrigerated food facilities across Europe. As compared with previous surveys of such nature, a relevant mapping of the energy consumption across the continent was preformed and reported for the first time.

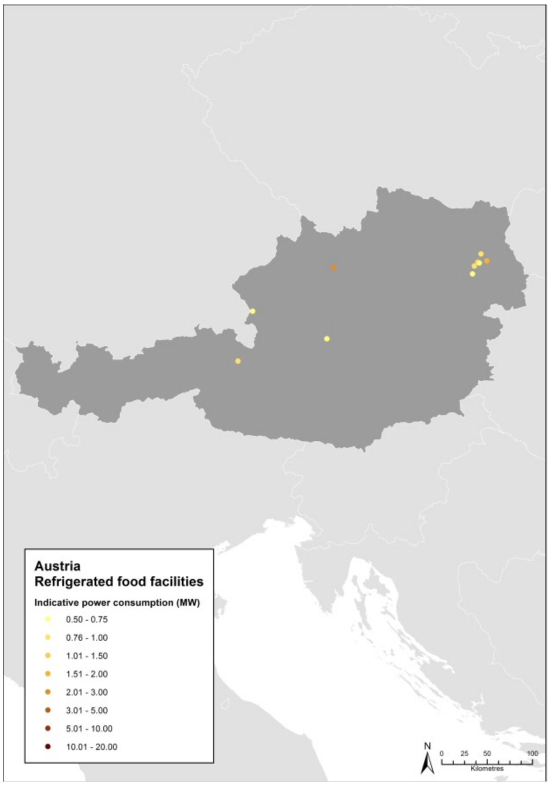
It can easily be noticed that the concentration of large refrigerated warehouses clearly depends on the population density and the production of perishable food commodities. Climate is another important factor, given the higher need for refrigeration capacities in the warmer regions of Europe than in the colder ones. However, the availability of such facilities is crucially depending on the overall technology level and economic development in a country or region, rather than merely on the necessity for refrigeration. Furthermore, the current trends in the sector are also influenced by the population growth, migration and urbanisation processes, dietary habits (e.g. increase use of ready-to-eat and chilled foods), which should further be analysed in terms of their economic implications and sustainability enhancement.

The information gathered ensures a science-based approach for integration of RES in refrigerated warehousing. Mapping the energy expenditure, along with the RES availability, permits to identify the EU regions and areas which are most promising for renewable energy projects in the industrial food refrigeration. Thus, this deliverable meets Objective 1 of WP2 by providing an indispensable tool for determining the potential of CryoHub as an emerging technology in both energy and food preservation sectors. Accordingly, the present study played a decisive role when determining the hosting company of the CryoHub demo site (*Golden CryoHub Champion).* I was decided that the web-based CryoHub mapping tool should be kept functional at least over the project duration to ensure a gradual update and enrichment of the CryoHub survey database.

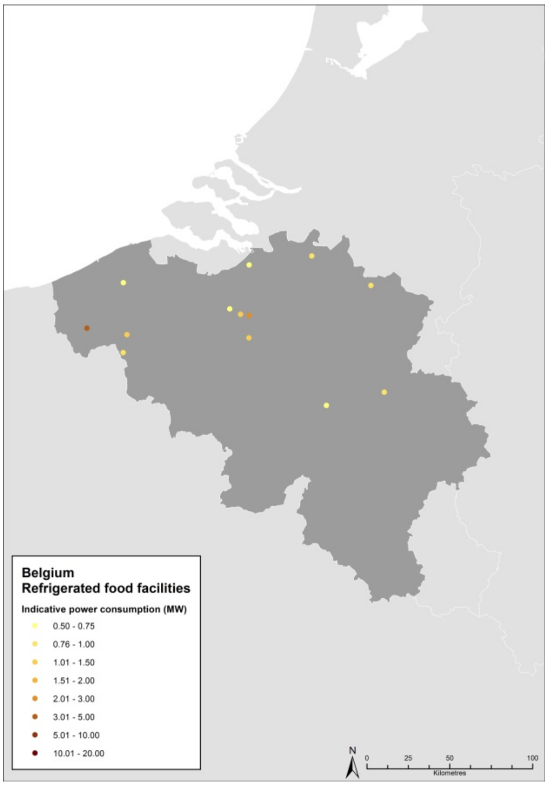
[1] IEE/09/849/SI2.558301 *"ICE-E: Improving Cold Storage Equipment in Europe"* – a project of Intelligent Energy for Europe (2010-2012)

Annex I - Mapping of refrigerated food facilities in individual EU countries

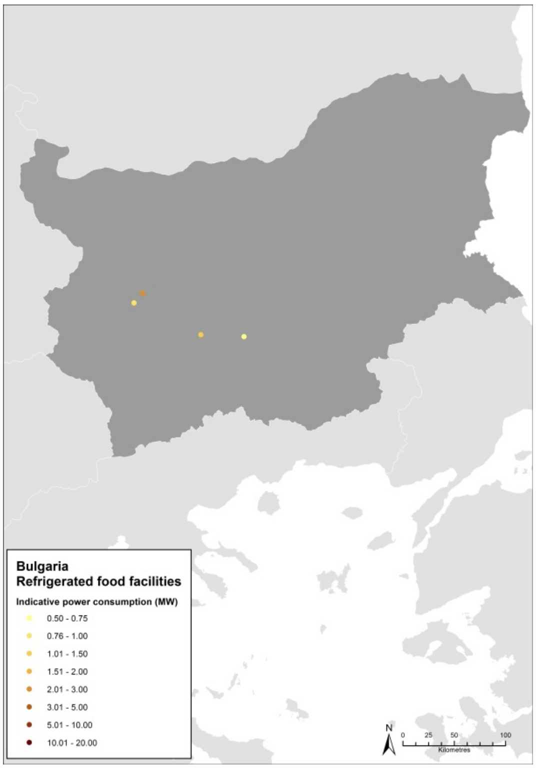
Austria



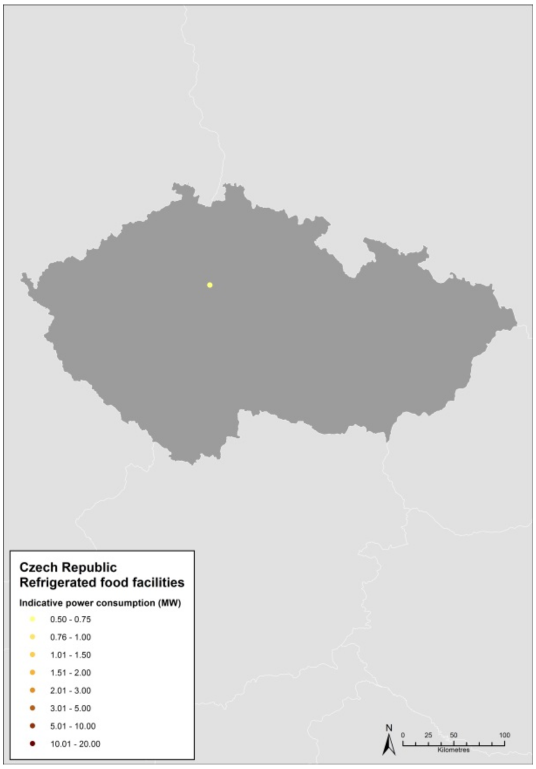
Belgium



Bulgaria

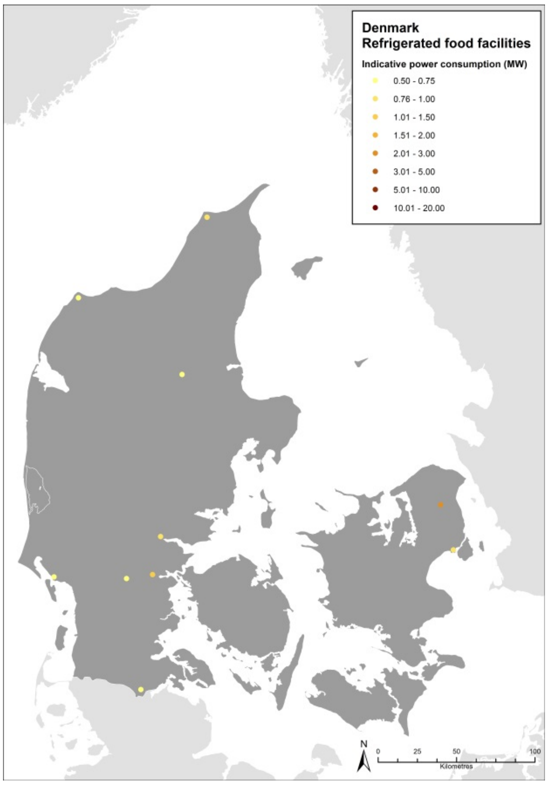


Czech Republic

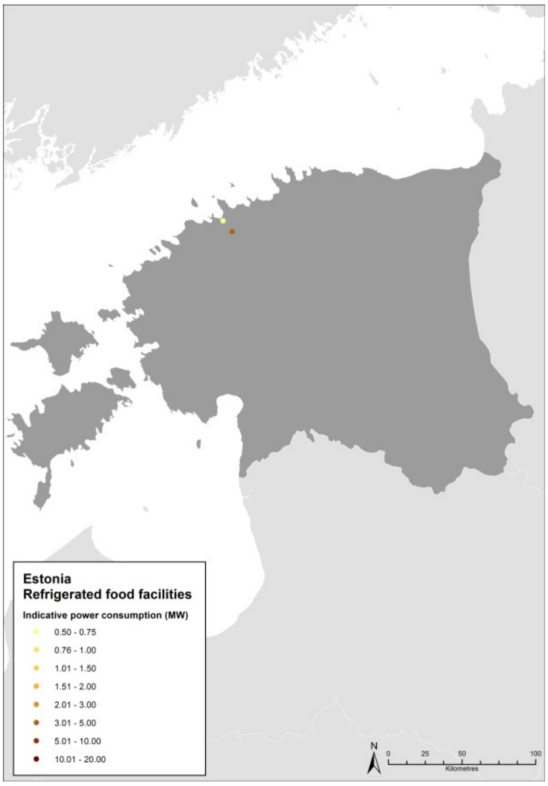


Annex I (*continued*)

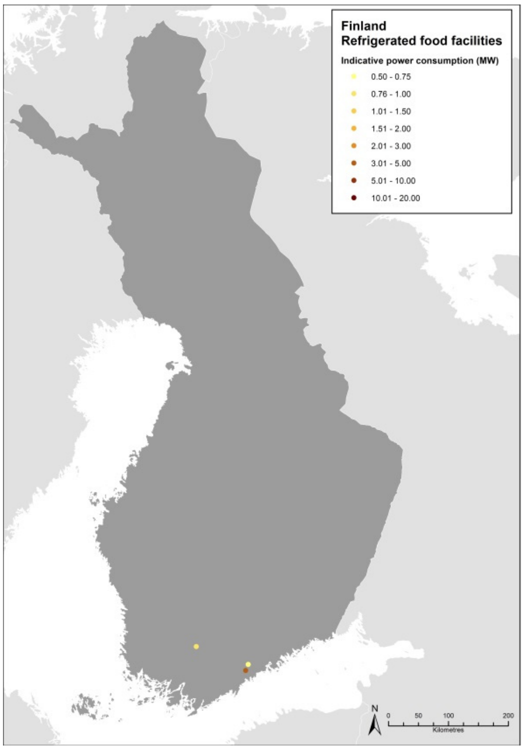
Denmark



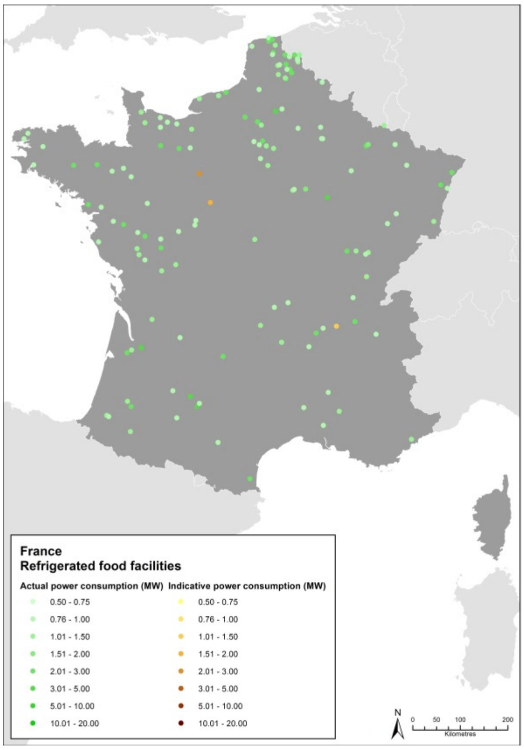
Estonia



Finland



France



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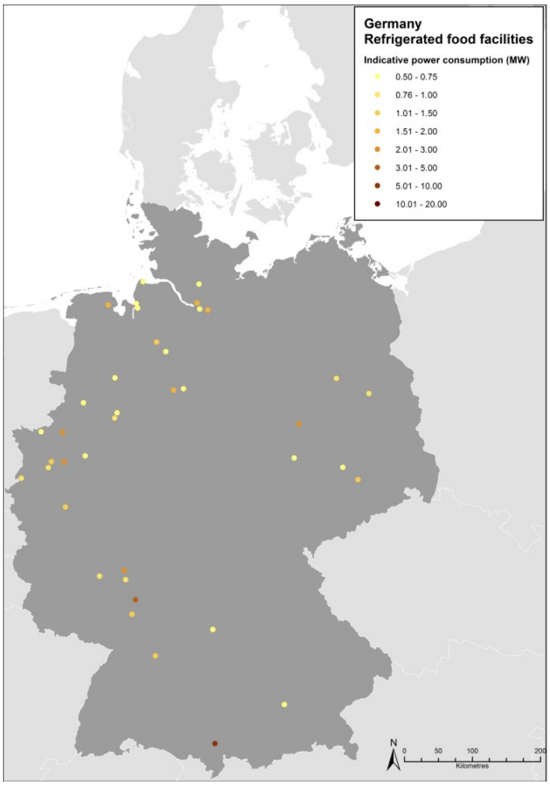
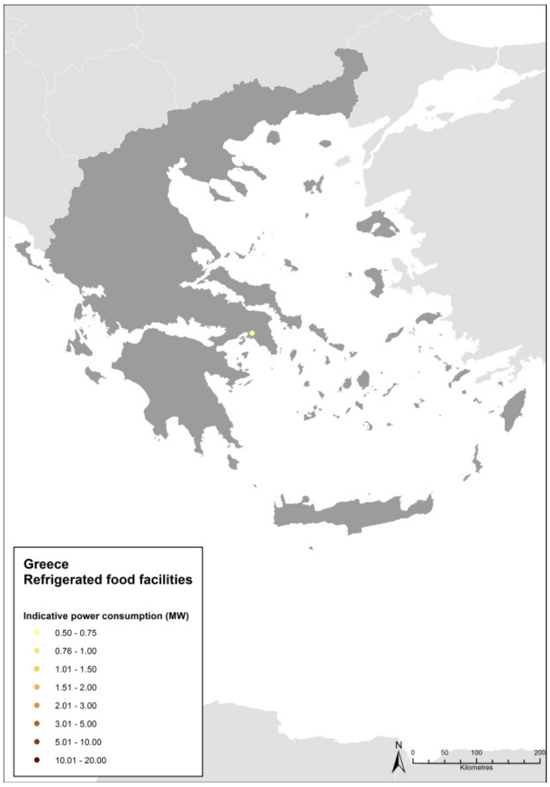
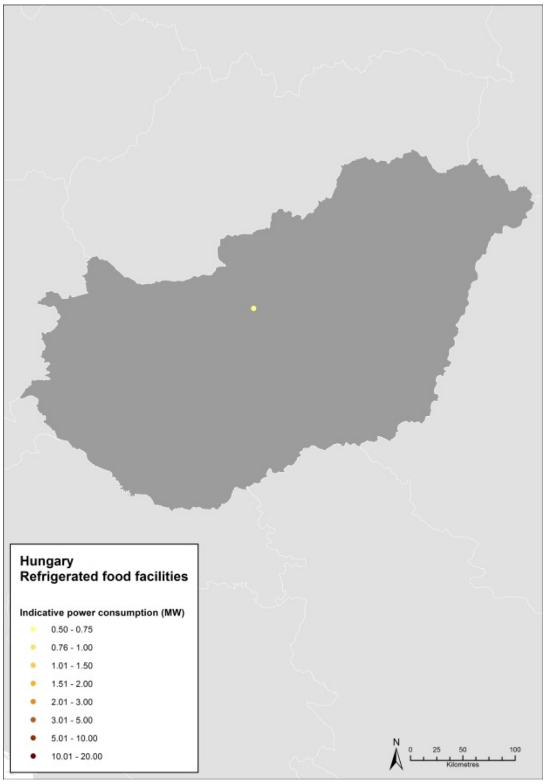
Germany



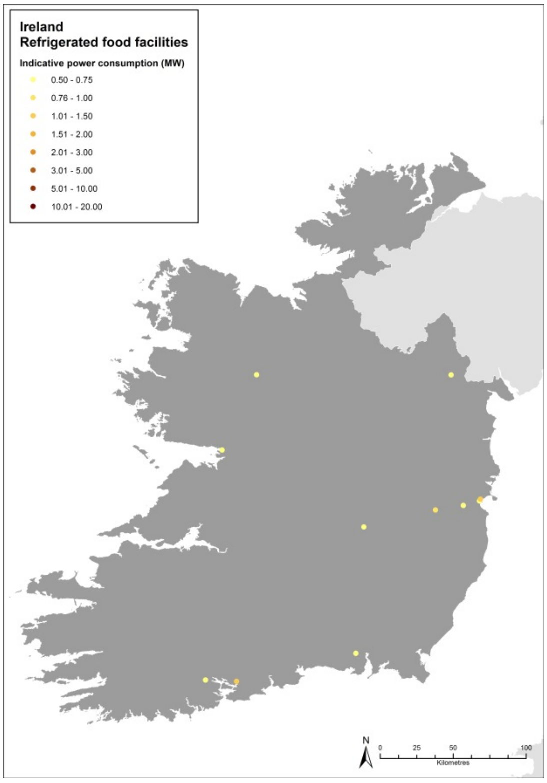
Greece



Hungary

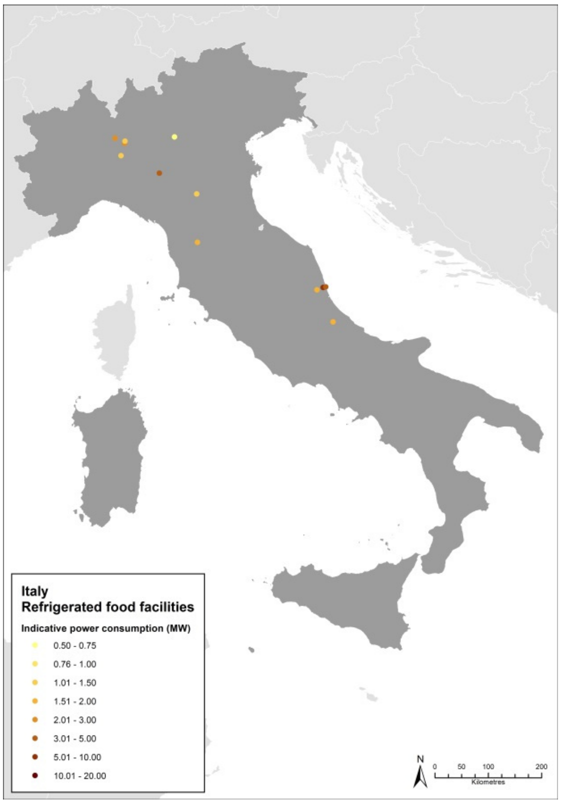


Ireland

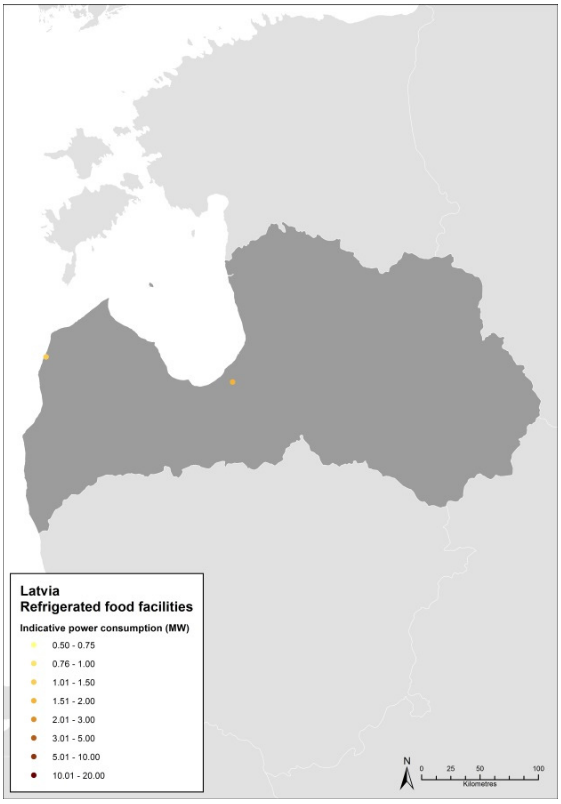


Annex I (*continued*)

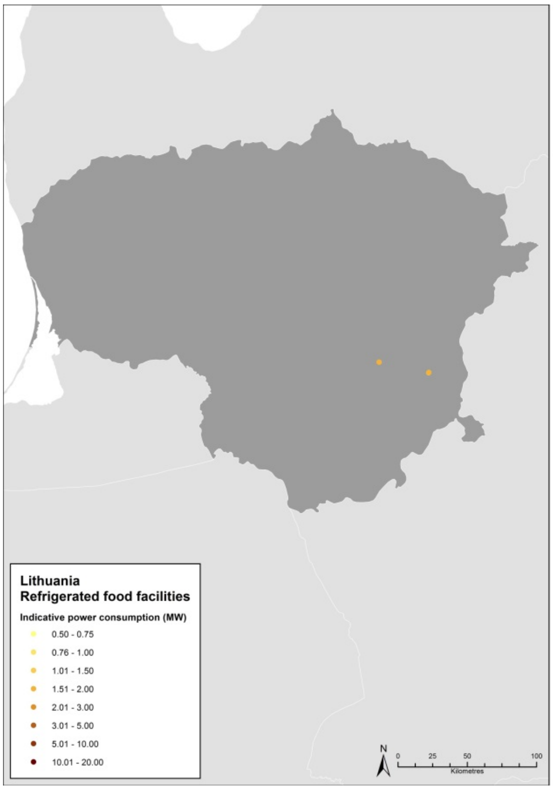
Italy



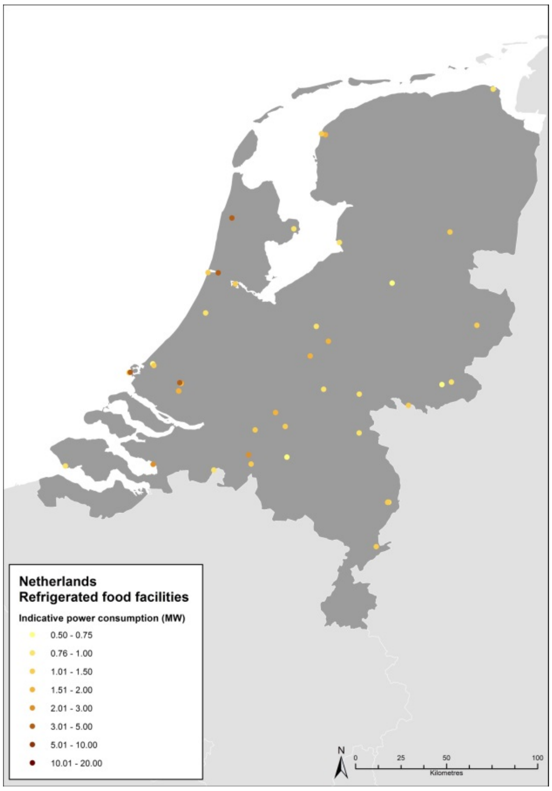
Latvia



Lithuania

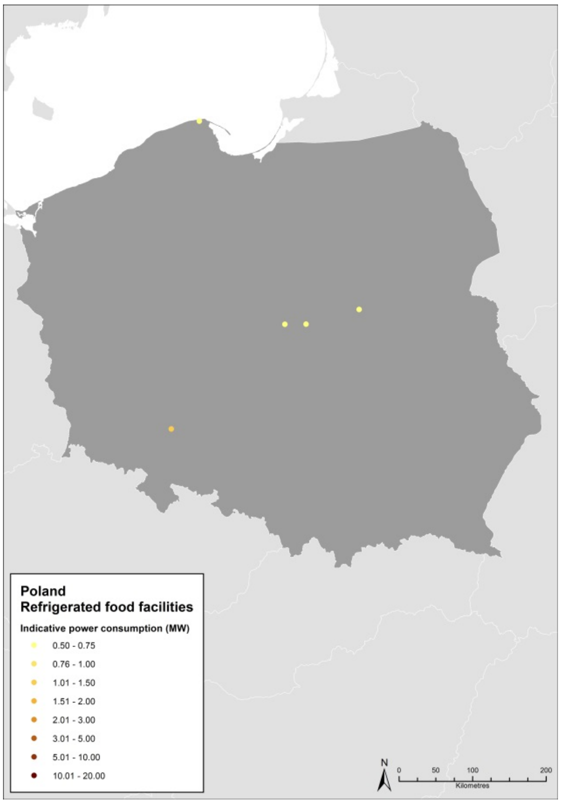


The Netherlands

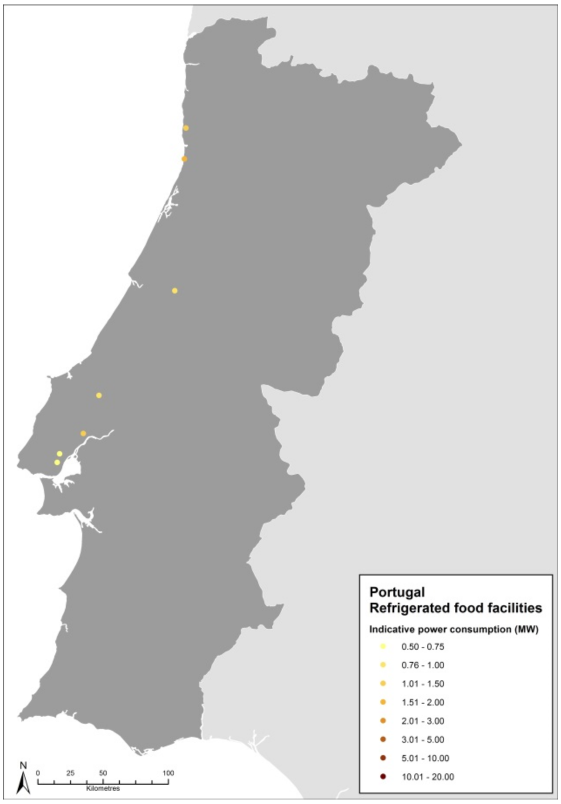


Annex I (*continued*)

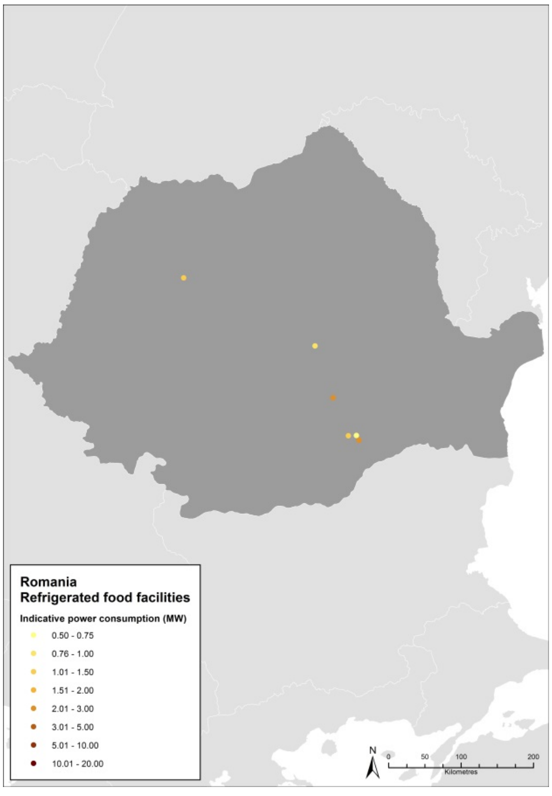
Poland



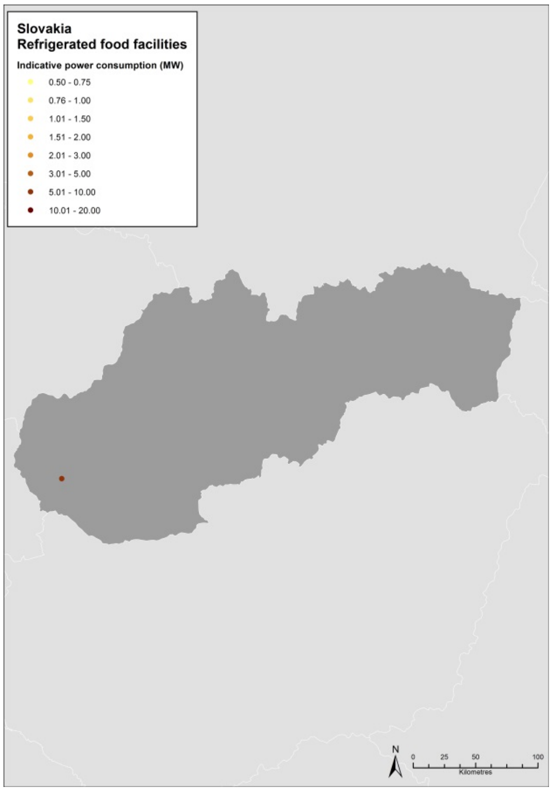
Portugal



Romania

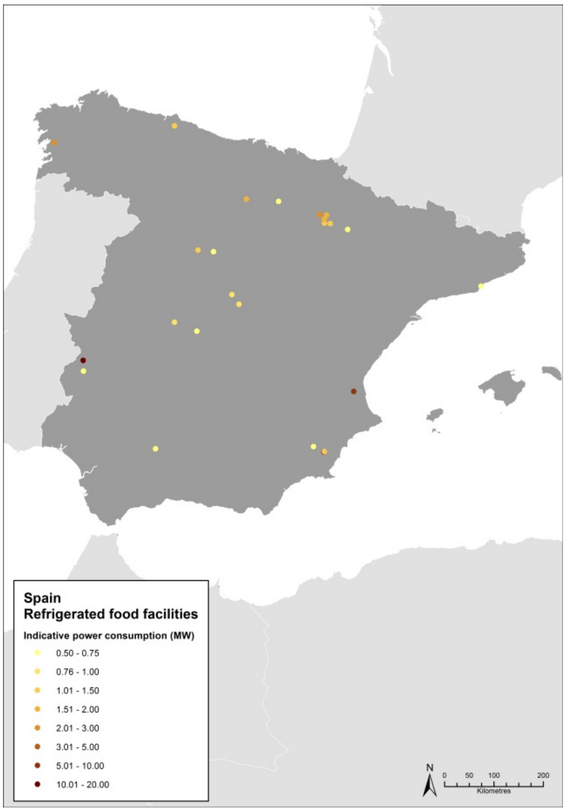


Slovakia

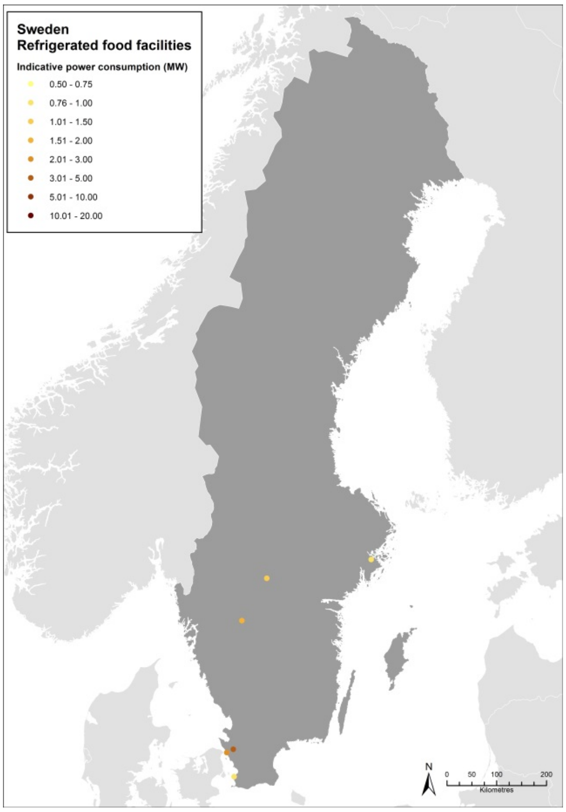


Annex I (*continued*)

Spain



Sweden



United Kingdom