



Energy use and retrofitting potential of heat pumps in cold climate hotels



S. Smitt^{a,*}, I. Tolstorebrov^a, P. Gullo^b, A. Pardiñas^c, A. Hafner^a

^a Norwegian University of Science and Technology, Department of Energy and Process Engineering, Kolbjørn Hejes Vei 1D, 7491, Trondheim, Norway

^b Technical University of Denmark, Department of Mechanical Engineering, Nils Koppels Allé 403, 2800, Kgs. Lyngby, Denmark

^c SINTEF Energy Research, Kolbjørn Hejes Vei 1D, 7465, Trondheim, Norway

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ABSTRACT

Tourism, and thereby hotels, play a crucial role in the European economy. The hotel sector features high energy consumption, which greatly contributes to the global warming effect. Thus, there is a need to investigate environmentally friendly technologies that have the potential to reduce energy usage within this sector. Information regarding the current status of the energy consumption in hotels is essential. Therefore, a study of 140 hotels in Norway and Sweden is presented in this paper to identify successful and sustainable measures to reduce energy consumption and related emissions.

The energy use, available energy sources and thermal systems in the hotels are studied over a five-year period to identify consumption trends. The results reveal that 70% of the hotels have a mean annual energy consumption between 150 and 250 kWh/m². A shift towards sustainable energy sources is observed in the hotels from 2015 to 2019, where application and overall consumption of district heating and cooling have increased, while electrical energy consumption has been reduced. District heating is the most prominent source of heating and is applied as the primary heat source in 70% of the hotels. The specific energy consumption for the group hotels that apply district heating is 218.9 kWh/m²/year, which is nearly 25% higher than the specific energy consumption of the 9% of hotels that apply heat pump solutions as a primary heat source. Thus, there is a potential to reduce the specific energy consumption in hotels. Two integrated transcritical carbon dioxide (CO₂) heat pumps were investigated as a sustainable measure to reduce energy consumption. The results reveal that a reduction of thermal energy consumption of approximately 60% can be achieved.

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1. Introduction

According to the EU strategic plan for heating and cooling in buildings, new and sustainable solutions for generating thermal energy must be applied to achieve the 2-degree goal of the Paris Agreement (EC, 2016). Presently, buildings account for more than 40% of the total end-use energy consumption in Europe (Rousselot, 2018). Approximately 1/3 of this energy consumption and related emissions is connected to the commercial sector (Eurostat, 2017). By implementing measures to increase efficiency and manage demands, it is estimated that energy saving of 30% can be achieved within the commercial sector (Economidou et al., 2011; EC, 2006).

Hotels are energy-intense buildings due to the nature of their operation and the behavior of the occupants (HES, 2011). The energy consumption in the hotel sector is high compared to other commercial sectors, such as the school and hospital sector (Pérez-Lombard et al., 2008). Many authors have tackled the challenge related to excessive energy consumption in hotels by applying alternative renewable energy sources and surveillance tools (Karagiorgas et al., 2006; Dalton et al., 2009; Aagreh and Al-Ghzawi, 2013). The largest contributor to excessive energy use within the hotel sector is hot water, space heating and cooling. In cold climates, it is estimated that approximately 61% of the total energy consumption in hotels is allocated to heating and cooling (Langseth, 2015). The application of conventional thermal energy sources in hotels is extensive, such as electric boilers in large inefficient central systems (Dalton et al., 2008b). A majority of hotels apply centralized heating stations, where thermal heat is generated and further transported throughout the building by a

* Corresponding author.

E-mail addresses: silje.smitt@ntnu.no (S. Smitt), ignat.tolstorebrov@ntnu.no (I. Tolstorebrov), parigul@mek.dtu.dk (P. Gullo), angel.a.pardinas@sintef.no (A. Pardiñas), armin.hafner@ntnu.no (A. Hafner).

Nomenclature

AC	Air-Conditioning
BIO	Biofuel
COP	Coefficient of Performance
DC	District Cooling
DH	District Heating
EL	Electricity
GO	Guarantees of Origin
GWP	Global Warming Potential
HDD	Heating Degree Days
HFC	Hydrofluorocarbons
HP	Heat Pump
MAAT	Mean Annual Air Temperature [°C]
N	Norway
NG	Natural Gas
R	Hydrofluorocarbons
S	Sweden
T	Temperature [°C]

secondary hydronic circuit.

Heating in Nordic hotels has been highly dominated by electric panels or hydronic heating through electric boilers, as a result of relatively low electricity prices caused by the availability of renewable energy sources. Norway is nearly exclusively supplied with electricity from hydro- and wind power, which share of the national production totaled approximately 98% in 2017 (Scheben et al., 2020). In Sweden, about 58% of the electric energy was renewable in 2018, mainly supported by hydro- and nuclear power (SEA, 2020). However, due to the high amount of energy guarantees of origin (GO) exported to Europe from both Norway and Sweden, the end-use CO₂ emissions related to electricity is estimated to 396 and 339 g CO₂-eq/kWh for 2019, respectively (NVE, 2020; Ei, 2020).

Fossil fuel-fired boilers are still the most applied source of heating in Europe despite high emissions (EC, 2016). Boilers are combustion machines that burn fuel, such as oil and natural gas (NG), for heating purposes. The related emissions from boilers applying oil and NG are 268 and 205 g CO₂-eq/kWh, respectively (SDHA, 2018). To reduce the environmental footprint, legislation and favorable incentives have been introduced in Norway and Sweden to encourage building owners to adopt sustainable heating solutions (Di Lucia and Ericsson, 2014; Norwegian Ministry of Environment, 2008; Swedish Ministry of the Environment, 2009). An environmentally friendly alternative to traditional fossil fuels is biofuels, which have related emissions of 15 g CO₂-eq/kWh (Gustafsson et al., 2016).

District heating (DH) has become a well-established heat source within the Nordic countries. DH is a network of insulated pipes, where heat is distributed to customers that are connected to the grid through in-house heat exchangers. The heat is generated at a centralized location near industrial processes with surplus heat, such as waste disposal plants. 49 and 22% of the heat in the DH networks in Norway and Sweden were generated from waste disposal in 2019 (Swedenergy, 2020; SSB, 2020). The related emissions from DH heat consumption in Norway and Sweden are calculated based on the 2019 DH mix and footprint values established by SDHA (2018). DH related emissions for Norway and Sweden are calculated to 115 and 63 g CO₂-eq/kWh, respectively. For the production of district cooling (DC), cold water from lakes and the sea is normally used. Alternatively, DC can be produced with the cooling effect from heat pumps during DH heat generation. The emissions related to the use of DC is estimated to 60 g CO₂-

eq/kWh (Dalin and Rubenhag, 2006).

In contrast with EL and DH, heat pumps upgrade heat from one temperature level to another. Thus, a considerably smaller amount of electricity is needed to generate thermal heat than for EL boilers. The performance indicator of a heat pump system, referred to as the coefficient of performance (COP), gives the amount of heat generated per unit of electricity. The COP of the heat pump is highly dependent on the supply and return temperatures in the heating system. The installation of thermal storage is an effective measure to improve the performance of heat pump systems. For hotels, thermal storage in the form of hot water tanks is applied to reduce peak loads (Tosato et al., 2019; Smitt et al., 2019).

The refrigerant, from which heat is transferred while undergoing the heat pump cycle, is selected based on characteristics like temperature, pressure, heat capacity, flammability and toxicity. The environmental impact of these fluids is referred to as global warming potential (GWP). Non-synthetic refrigerants that are naturally occurring, such as carbon dioxide (CO₂), ammonia and propane, have marginal GWPs (Lorentzen, 1995). Synthetic refrigerants, such as hydrofluorocarbons (HFCs), have high GWP and contribute significantly to global warming (Abas et al., 2018). Therefore, industrial and scientific efforts have been invested in improving heat pump systems with natural refrigerants and identifying new areas of applications, such as the hotel sector. Additionally, national legislation, governmental economical incentives and reduced operational costs are strengthening the position of efficient and environmentally friendly thermal systems (Norwegian Ministry of Environment, 2008; Swedish Ministry of the Environment, 2009). Moreover, the environmental aspect of tourism is becoming important for guests when selecting hotels (HES, 2011). Nearly 80% of potential guests believe that renewable energy is important for European tourist accommodations (Dalton et al., 2008a). Yet, reducing the operational cost is undeniably the biggest incentive among hotel owners to introduce environmentally-friendly initiatives (Bohdanowicz, 2006).

The European hotel sector has increased during the last decade with an annual market growth between 7 and 13% (PwC, 2018). Although heavily affected by the COVID-19 epidemic, it is expected that the European hotel sector will recover and that the number of international visitors will increase by 43 million a year until 2030 (UNWTO, 2020; UNWTO, 2019). In order to reduce the energy consumption of this growing sector, sustainable solutions for thermal energy production must be applied. Information regarding the current status of energy consumption and thermal heating in hotels is therefore essential. To the best of the authors' knowledge, no large-scale investigations of Nordic hotels have been conducted in the last decade. Furthermore, no analyses of thermal systems in hotels have been performed to differentiate energy consumption and emissions according to thermal heat source. This paper presents a study of 140 hotels in Norway and Sweden, where energy consumption, energy source and thermal systems are evaluated over a five-year period.

The scope of this paper is to evaluate key performance indicators related to energy consumption in Norwegian and Swedish hotels. The annual energy consumption per heated floor area (kWh/m²/year) and energy consumption per guest-night (kWh/guest-night/year) are applied to evaluate the energy performance of the hotels. Energy usage based on different activities in the hotel buildings is beyond the scope of the research. The results are reviewed over a five-year period to reveal the energy-related trends and the long-term dynamics of the sample hotels. The focus of the study is the thermal heating systems, which are the main contributing source of excessive energy usage in cold-climate hotels. The environmental impact of different thermal solutions in hotels are evaluated by the use of the CO₂-equivalent carbon footprint values and the energy source-specific consumption in

each hotel. Two of the hotels in this study are among the first in Europe to implement thermal solutions with integrated CO₂ heat pumps, both heating and cooling. The energy performance and the sector-wide implementation potential of the systems are evaluated in terms of energy savings.

2. Methods and materials

2.1. Data collection

The sampled hotels presented in this analysis are located in Norway and Sweden. The sample group consists of 140 hotels. As a whole, the Norwegian and Swedish hotel sectors consist of nearly 3900 hotels (Horwath HTL, 2010). To increase the validity of the results, only hotels with automatic energy logging surveillance systems were included in this study. Energy data from the hotels have been collected via several web-monitoring services, such as the software IWMAC (IWMAC, 2019). The energy data contain information about the specific energy use according to the energy source in each hotel, e.g. DH and electricity. The data are presented on an annual basis. The performance of the hotels is considered over a five year period, from 2015 to 2019. Hotels with compromised energy data for specific years, due to e.g. energy system maintenance or facility closure, have been excluded from the analysis for that particular year. Information regarding installed energy systems, energy consumption and guest-nights have been collected through surveys. Further, the information has been compared and validated with logged data from each specific hotel.

2.2. Hotel classification

Fig. 1 illustrates the arrangement of the climate zones in Norway and Sweden according to their respective national standards. Norway (N) is divided into seven climate zones, primarily based on coastal, inland and highland climates, ranging from south to north (Tokle and Tønnesen, 1999).

The four Swedish (S) climate zones are established primarily based on latitude and are defined in the 2015 Swedish building code (Boverket, 2015). Climate zone characteristics, mean annual air temperature (MAAT) and the number of hotels in each zone are listed in Table 1. The number of hotels are equally distributed between Norway and Sweden, with 70 in each country. The location of the hotels, according to the different climate zones, is consistent with the population density of each country.

Approximately 10% of the Norwegian population and 6% of the Swedish population reside in the northern climate zones (SSB, 2014; SCB, 2020a). Consequently, a mere 12% of the sample hotels are located in the northern part of the countries (N6, N7 and S1). 60% of the sample hotels are located in the southern regions of Norway and Sweden, in zones N1, N2 and S3, due to the close proximity to major cities.

Heating degree days (HDD) are applied to compare energy consumption in buildings, independent of variations in annual ambient temperature and thus heating consumption. The HDD values for the different zones are calculated with a standard threshold of 17 °C, as defined by Thom (1954). Table 2 lists the annual specific adjustment factor [-] for heating, which is defined as the HDD for a particular year, divided by HDD of a standard year. The values indicate the relative coldness for a particular year related to a normal year. The HDD data for Norway have been obtained from Enova SF (2020), whilst the commercially available Swedish climate data have been provided by The Swedish Meteorological and Hydrological Institute. The heat energy consumption in the hotels has been corrected according to their zone-specific adjustment factors. As illustrated in Table 2, all zones have

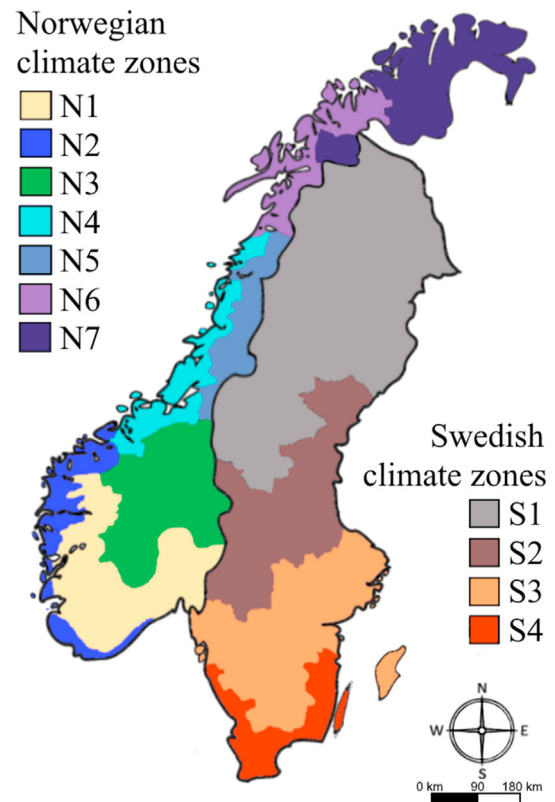


Fig. 1. Norwegian and Swedish climate zones.

Table 1

Description of climate zones and the location of the hotels.

Zone	Description	MAAT*	No. of
		[°C]	hotels
N1	Southern Norway, coastal climate	5.1 ^a	27
N2	Southern Norway, inland climate	7.1 ^a	24
N3	Southern Norway, highland climate	2.3 ^a	4
N4	Central Norway, coastal climate	5.4 ^a	8
N5	Central Norway, inland climate	3.0 ^a	0
N6	Northern Norway, coastal climate	3.8 ^a	7
N7	Northern Norway, inland climate	0.7 ^a	0
S1	Northern Sweden, inland climate	-2.0–0.0 ^b	10
S2	Central Sweden, inland climate	2.0–4.0 ^b	9
S3	Southern Sweden, inland climate	4.0–6.0 ^b	34
S4	Southern Sweden, coastal climate	6.0–8.0 ^b	17

* Mean annual air temperature.

^a Tokle and Tønnesen (1999).

^b Lundström et al. (2018).

experienced elevated ambient temperatures during the five-year period, as the adjustment factor is below 1.00.

All sample hotels have a heated floor area, henceforth referred to as floor area, in the range of 1446 to 38,000 m². The hotels have been arranged according to floor area to evaluate the energy performance of small, medium and large-sized hotels. As no standard for hotel classification exists in Norway and Sweden, a range of floor area has been selected for the classification, in preference to the number of rooms. This is done to best illustrate the energy consumption in a variety of hotels: small city hotels with many rooms to large spa hotels with a moderate number of rooms. However, the hotel sizes (small, medium and large) correlate to the number of hotel rooms in the range of 34–99, 100–299 and above 300. The number of hotels in each category is listed in Table 3.

Table 2
Adjustment factor for climate zones in Norway and Sweden related to climate data from 1981 to 2010.

Zone/Year	2015	2016	2017	2018	2019
N1	0.884	0.926	0.920	0.924	0.907
N2	0.885	0.928	0.913	0.931	0.911
N3	0.892	0.942	0.939	0.940	0.924
N4	0.873	0.939	0.930	0.950	0.944
N5	0.895	0.947	0.915	0.986	0.959
N6	0.868	0.926	0.953	0.962	0.985
N7	0.896	0.900	0.950	0.938	0.986
S1	0.892	0.950	0.971	0.968	0.981
S2	0.892	0.936	0.950	0.942	0.932
S3	0.885	0.937	0.927	0.916	0.896
S4	0.884	0.924	0.916	0.891	0.860

3. Results and discussion

3.1. Energy analysis

The energy data from the hotels have been analyzed and are presented in this section. Fig. 2 shows the five-year mean annual energy consumption per floor area for all the sample hotels (kWh/m²/year). When observing the energy consumption for all the hotels, it can be seen that about 40% have an energy consumption in the range of 175–225 kWh/m². The majority of the hotels, approximately 70%, have an energy consumption between 150 and 250 kWh/m²/year. The mean energy consumption for all hotels is calculated to 213 kWh/m²/year, which is slightly low when compared with earlier findings in other large-scale investigations of Nordic hotels. A comprehensive study by Bohdanowicz et al. (2005) found that a sample of hotels located in Sweden had an annual specific energy consumption of approximately 280 kWh/m²/year in 2003. SEA (2011) concluded that a mean energy consumption of 250 kWh/m²/year applies for hotels in Sweden. At a later time, Langseth (2015) suggested that a mean energy consumption of 240 kWh/m²/year is representative for Norwegian hotels. It is reasonable to assume that the energy consumption in Nordic hotels has decreased during the last decade, due to an increased focus on energy management, innovations in building technologies and legislative restrictions.

The energy consumption distribution profile for small and large-sized hotels are considerably shifted compared to the distribution for all the hotels. This is in agreement with the mean average consumption for the small, medium and large-sized hotels, which is calculated to 237, 209 and 192 kWh/m²/year, respectively. Thus, the results indicate an inverse relationship between hotel size and specific energy consumption, which can be explained by the typical energy systems installed in different sized hotels. Smaller hotels are often located in city centers, where space, building mass and investment costs limit the economical advantages of replacing outdated thermal systems. Larger hotels consume considerable amounts of energy and therefore deal with high operational costs. The most efficient energy systems are therefore installed in this category of buildings, as the potential savings are substantial along with shorter payback time. When investigating the energy

Table 3
Hotel classification.

Category	Size	No. of hotels
Small	floor area ≤ 5000 m ²	34
Medium	5000 m ² < floor area ≤ 16,000 m ²	83
Large	floor area > 16,000 m ²	23

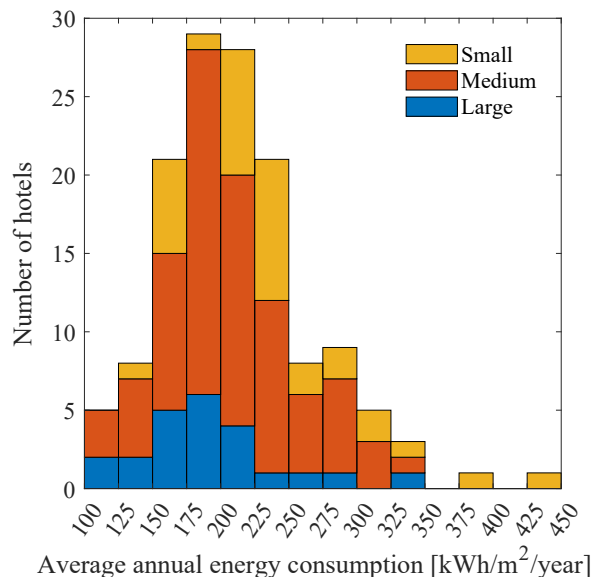


Fig. 2. Average annual energy consumption for the hotels per square meter floor area (2015–2019).

consumption of the hotels according to country, the Norwegian and Swedish hotels were found to have an annual specific energy consumption of 203 and 222 kWh/m²/year, respectively. The difference can be attributed to the fact that 60% of small-sized hotels in this investigation are located in Sweden.

Fig. 3 shows the average annual energy consumption of the hotels per guest-night, where 55% of the hotels display a specific consumption in the range between 20 and 40 kWh/guest-night/year. The mean annual energy consumption for all the sample hotels is calculated to 37.8 kWh/guest-night/year.

Similar to Fig. 2, the distribution according to different hotel sizes is also illustrated in Fig. 3. The mean annual energy consumption is calculated to 29.2, 39.8 and 43.4 kWh/guest-night/year, for small, medium and large hotels, respectively. Thus, the opposite trend is observed when evaluating the specific energy consumption in terms of guest-nights and floor area. As can be observed in Fig. 3, the specific energy consumption per guest-night increases with hotel size, being that large hotels consume nearly 48% more than hotels that are categorized as small. Specialized hotels, such as spa and conference hotels, are generally of larger size and require more space and energy per guest due to the nature of the facilities.

Table 4 lists the mean annual energy consumption per guest-night, which is steady between 38 and 41 kWh/guest-night/year for the years 2015–2018. A small reduction in specific energy consumption per guest-night is observed in 2019, which can be attributed to the increase in the average number of guest-nights for that particular year.

The mean annual energy consumption (GWh/hotel), along with the related emissions (kg CO₂-eq/hotel), are included in Table 4. For the average hotel, the energy consumption is in the vicinity of 2 GWh/year. The energy consumption and the emissions related to hotel size is shown in Table 5. On average, large hotels consume more than 4.5 GWh/hotel/year, which is five times more than small-sized hotels. The same trend is observed for the total emissions, where small and large hotels emit, on average, 209,885 and 1,166,734 kg CO₂-eq/hotel/year, respectively. The mean annual emissions from energy consumption in the hotels vary with approximately 30,000 kg CO₂-eq/hotel during the five years, as

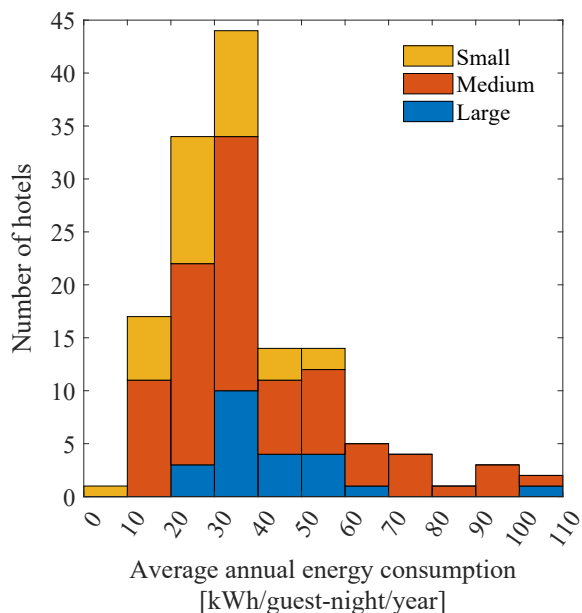


Fig. 3. Average annual energy consumption for the hotels per guest-night (2015–2019).

shown in Table 4.

The highest amount of emissions occurred in 2018, where more than 560,000 kg CO₂-eq on average were emitted from each hotel. Between 8.4 and 9.7 kg CO₂-eq is recorded per guest-night during the five-year period. The range of emissions related to the hotel sizes is shown in Table 5 and vary from 7.7 to 13.7 kg CO₂-eq/guest-night/year. The values presented in this study are higher than emissions reported for the Nordic hotel sector, which generally vary between 3.3 and 6.0 kg CO₂-eq/guest-night (Thompson, 2019; Larsson and Kamb, 2018). However, the contribution of energy GO export between nations was not accounted for in these studies, only each countries' standard calculated emissions per kWh consumed. This presents a challenge, as each country tend to calculate the energy-related emission with favorable values. Thus, some country standard values for emissions include the energy GO related emission and some do not. As explained in Section 1, GO related emissions are applied in this study to give a comparative account for the large-scale environmental impact from different energy sources and thereby the impact from different thermal systems in hotels.

The distribution of the energy consumption according to source is shown in Fig. 4, while the available energy sources in the hotels are illustrated in Fig. 5. The category *other* includes burners for oil, natural gas and biofuel. The energy consumption of this group is stable at around 1% for the whole period, as shown in Fig. 4. A slight

Table 4
Mean annual energy indicators for the sample hotels.

Value/Year	2015	2016	2017	2018	2019
Hotels analyzed [-]	96	125	136	140	134
Guest-nights [guest-night/hotel]	54,772	58,178	59,472	60,382	64,377
Energy consumption [GWh/hotel]	1.8	2.1	2.0	2.1	2.0
Energy consumption per guest-night [kWh/guest-night]	38	39	38	41	36
Energy consumption per floor area [kWh/m ²]	195	214	214	218	211
Emissions from energy consumption [kg CO ₂ -eq/hotel]	529,739	567,132	548,069	560,371	538,116
Emissions per guest-night [kg CO ₂ -eq/guest-night]	9.7	9.7	9.2	9.3	8.4

Table 5
Mean energy indicators for the hotels categorized by size based on data for all five years (2015–2019).

Value/Hotel size	Small	Medium	Large
Energy consumption GWh/hotel/year	0.8	1.9	4.5
Emissions kg CO ₂ -eq/hotel/year	209,885	508,232	1,166,734
kg CO ₂ -eq/guest-night/year	7.7	11.0	13.7

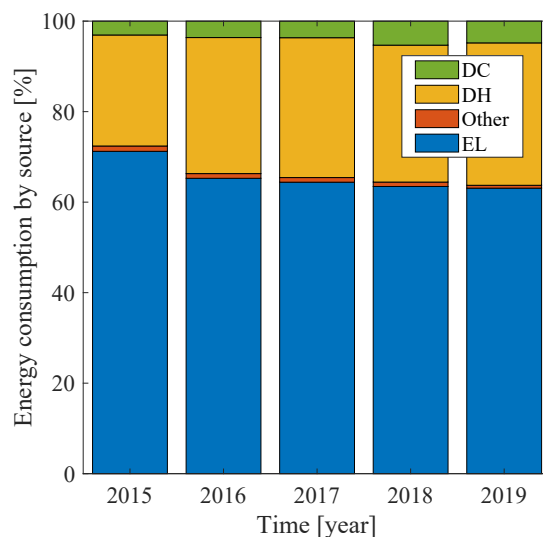


Fig. 4. Energy consumption by energy source in the hotels [%].

increase in the use of other energy sources is observed in Fig. 5, which is mainly

attributed to newly installed bio-fuel systems. EL in Fig. 4 constitutes the largest share of the energy consumption each year and includes the total electricity consumption in the hotels. All processes that require electricity within the buildings are included in this category. For certain hotels, this entails electricity for electric boilers, heating panels, heat pumps and air-conditioning (AC) units. Approximately 71% of the total energy consumption in 2015 was recorded as EL. However, an 8% decrease in the total share of EL energy consumption is observed over the five-year period. This is in agreement with the data presented in Fig. 5, which shows that the amount of hotels with EL-only access is almost halved, from 37.5% in 2015 to 19.4% in 2019. During the same period, the number of hotels connected to DH and DC networks has increased by 18.0 and 10.9%, respectively. This trend is reflected in the percentage DH consumption to the total energy usage in Fig. 4, which shows an increase of 7% over the five years, from 24.5 to 31.5%. Thus, many hotels have replaced electric thermal heating systems in favor of

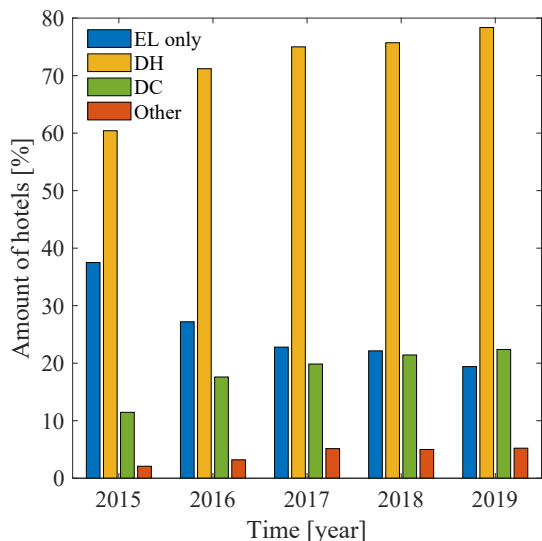


Fig. 5. Available energy sources in the hotels.

DH during this period. Likewise, DC energy consumption increased by about 2% from 2015 to 2019. Similar trends have been documented within the Swedish non-residential buildings sector, where the total share of DH consumption has increased by 7.6% from 2005 to 2016 (SEA, 2017).

Fig. 6 shows an overview of the primary and secondary thermal heating systems installed in the sample hotels. The four primary thermal heating systems that are applied in the hotels are DH, HP solutions, NG and EL, in which the latter includes both electric boilers and electric panels. DH represents the

largest group of the primary thermal energy system, as 98 of the 140 hotels (70%) use DH as a primary heat source. DH is used as a secondary or back-up thermal energy system in four hotels. This corresponds to the data presented in Figs. 4 and 5, which illustrate high consumption levels of DH and a high degree of DH availability

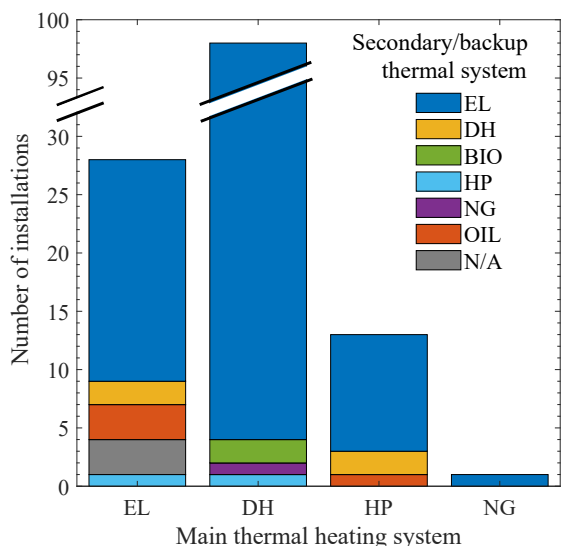


Fig. 6. Overview of primary and secondary thermal heating systems in all hotels (2019).

in the different hotels. The second most applied primary energy system is EL, with 28 hotels (20%). 9 of these hotels have an alternative backup heat source, with OIL and DH being the most prominent. Only three hotels lack information about secondary systems, denoted N/A in figure Fig. 6. Despite providing relatively low system efficiencies and a high carbon footprint, EL heating is reliable and easily implemented. EL is, therefore, favored as a secondary/peak heating source and applied as such in 124 hotels (88%). As shown in Figs. 6 and 13 hotels use HP systems as their primary heating system. This category includes stand-alone heat pump units, integrated heat pump and chiller units and large central heat pump units that supply heat to a collective of buildings. Only two of the hotels in this category apply natural working fluids, which have a minimal GWP compared to the HFC working fluids (Bolaji and Huan, 2013). Two additional heat pumps are applied as secondary system solutions, mainly for domestic hot water production.

Table 6 lists key energy indicators, such as energy use and emissions, with respect to the four primary thermal systems shown in Fig. 6.

The sole hotel that represents the NG primary systems has the largest area-specific energy consumption of the groups, at a value of 236.7 kWh/m²/year. The DH primary thermal system group includes 70% of the hotels and is the most applied heating system in both countries. The mean specific energy consumption for this group is among the highest at a value of 218.9 kWh/m²/year. However, the mean guest-specific energy consumption of DH systems is only 35.6 kWh/guest-night/year, which is lower than EL and NG based primary systems. The group of hotels that apply EL as their primary thermal heating system have the highest recorded guest-specific energy consumption at 43.1 kWh/guest-night/year, and area-specific energy consumption of 204.9 kWh/m²/year. Thus, an inverse relationship exists between the specific energy consumption of the two groups, EL and DH, which can be explained by trends shown in Figs. 2 and 3. The group of hotels that apply EL as their primary thermal system are generally of medium-to-large size, whereas small-to-medium sized hotels are over-represented in the DH primary heat source category. As listed in Table 6, hotels that apply EL as their primary systems perform poorly in regards to energy-related emissions. The mean specific emissions from this group are 79.8 CO₂-eq/m² and 16.8 CO₂-eq/guest-night, which is considerably higher than for the alternative heating systems. The superior thermal solution, in terms of emissions, is DH primary systems. Both the area and guest-related emissions are considerably lower for the group of hotels with DH primary systems, at values of 48.7 CO₂-eq/m² and 8.3 CO₂-eq/guest-night. The low emissions of DH compared to the alternative systems are directly tied to the electricity GO export, which elevates the specific emissions of EL and HP primary systems.

The HP based system is the most efficient primary thermal system of the alternatives presented in Table 6. The hotels that are categorized within this group have a mean specific energy consumption of 175.4 kWh/m²/year and 34.0 kWh/guest-night/year. Thus, the hotels equipped with HP as the primary systems consume

Table 6 Mean energy indicators with respect to primary thermal system (2015–2019).

Value/Main system	EL	DH	HP	NG
<i>Energy consumption</i>				
kWh/m ²	204.9	218.9	175.4	236.7
kWh/guest-night	43.1	35.6	34.0	36.3
<i>Emissions</i>				
kg CO ₂ -eq/m ²	79.8	48.7	62.8	64.4
kg CO ₂ -eq/guest-night	16.8	8.3	11.8	9.9

14.6% and 19.9% less kWh/m²/year compared with EL and DH, respectively. The heat pumps that constitute the HP group are of different design and year of installation. The efficiencies of the heat pumps are not accounted for in this study. However, the recent development of heat pump technology affirms that heat pump solutions for hotels can achieve a considerably larger amount of energy savings when compared with EL and DH thermal systems. Bianco et al. (2017) illustrated how renewable technologies, such as heat pumps, could decrease the energy consumption and related emissions within the Italian hotel sector by 13% (1.6 TWh). Yet, not all working fluids are preferred for heat pumps in hotels, due to safety restrictions on account of toxicity and flammability (EN 378–1:2016). Additionally, many non-natural refrigerants, like HFC, are in the process of being phased out in the EU and Scandinavia (Heath, 2017). CO₂ is a natural and safe working fluid, which application in heat pumps is thoroughly accepted and documented (Rony et al., 2019; Zhang et al., 2015). If design properly, CO₂ heat pumps are efficient, safe, and sustainable solutions for thermal heating in hotels (Nekså, 2002; Smitt et al., 2020; Tosato et al., 2019; Smitt and Hafner, 2019). Section 3.2 presents the operational results of two hotels implemented with such thermal systems.

3.2. CO₂ heat pump solutions for hotels

Two different schematic designs of integrated transcritical CO₂ heat pump systems are shown in Fig. 7.

The system illustrated in Fig. 7(a) consists of four separate parallel units and has a total heating capacity of 800 kW. The system was installed in 2019 in hotel A, which is located in climate zone N2. The hotel was built in 1990 and has a floor area of 13,500 m². The CO₂ system collects heat from seawater through two titanium heat exchangers and lifts this to a temperature of approximately 80 °C. Through the secondary system, heat is supplied for space and water heating. The hot water system is equipped with 10 m³ thermal storage and supplies hot water for guests in the main building and

the hotel water park. Additionally, heat is exported from the hotel to a nearby gym. The space heating circuit supplies heat to both the hotel and the water park, as well as heating of the swimming pool. An 8 m³ thermal storage is included in this circuit as a heat buffer to reduce the return temperature from the hotel to the CO₂ heat pump. This is imperative in transcritical CO₂ systems to achieve high efficiency and is described thoroughly in the literature (Minetto et al., 2016; Tamaro et al., 2016). Fig. 7(b) illustrates the integrated CO₂ system that was installed in hotel B in 2018, which is located in zone N4. The hotel is 9000 m² and the thermal system consists of a single CO₂ unit that supplies heat to space heating and the 6 m³ hot water storage. The heating and AC cooling capacity of the system is 280 and 75 kW, respectively. A detailed description and analysis of the system installed in hotel B is given by Smitt et al. (2020). Though different in design, a key feature in both transcritical CO₂ systems is the thermal storage, which acts as a buffer that allows for flexible operation of the thermal system. Thus, peak power demands are reduced by accumulating heat over time, rather than supplying peak-heating to meet the instantaneous demands.

Fig. 8 shows the specific energy consumption of hotel A for the last five years. Hotel A was equipped with an electric boiler before the CO₂ heat pump was installed in November 2019. For the year 2019, hotel A achieved a reduction in the overall energy consumption in the hotel of 26.3%, which corresponds to a reduction of 1.2 GWh/year or 88.6 kWh/m²/year.

In order to indicate the performance of the CO₂ system after the commissioning period, the energy consumption and guest-nights for selected months in 2020 are shown in Fig. 9. The mean monthly energy consumption and guest-nights from 2015 to 2019 are given as a reference. Months of operation that were influenced by the COVID-19 outbreak are not included in Fig. 9. All selected months in 2020 demonstrate a reduction in the specific energy consumption compared to the mean values (2015–2019), despite the increase in guest load over this period. The largest change in specific energy consumption is observed during the month of September when a 51.3% reduction in energy consumption is achieved. July represents the month with the lowest reduction in total specific energy consumption, at -31.6% compared to the mean value. It should, however, be noted that hotel A experienced a 32.9%

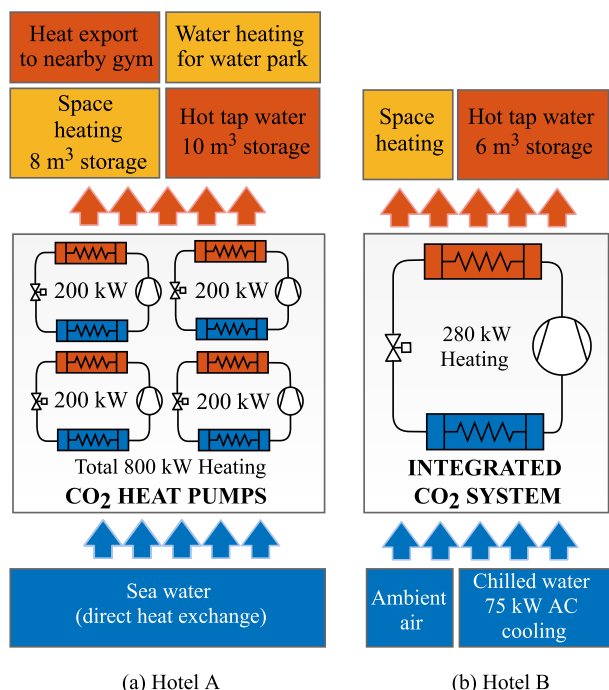


Fig. 7. Schematic of thermal systems installed in (a) hotel A and (b) hotel B.

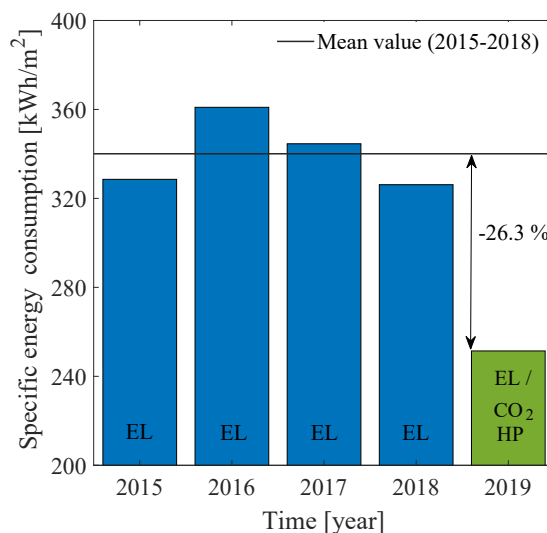


Fig. 8. Energy consumption of hotel A for the years 2015–2019. The reduction in energy usage after retrofit in 2019 is related to the mean of the four previous year.

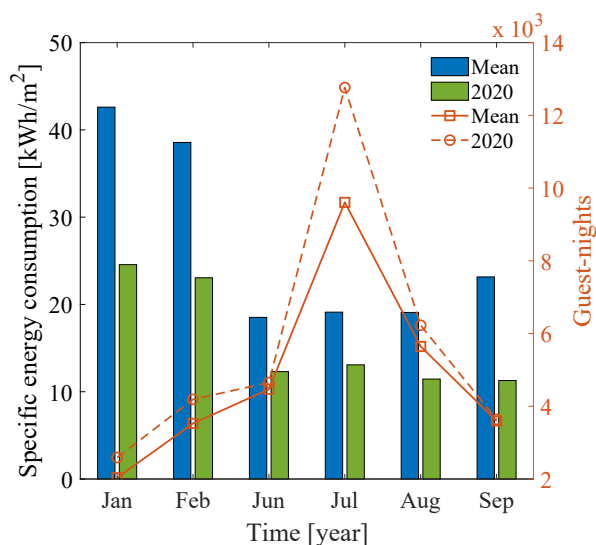


Fig. 9. Specific energy consumption and guest-nights for hotel A for selected months in 2020. Mean values for energy consumption and guest-nights for the period 2015–2019 are used as reference.

increase in the guest-load during July 2020. The average monthly savings based on the selected months in Fig. 9 is calculated to 39.8%. If the monthly reduction in specific energy consumption is extrapolated to the annual performance of the thermal system, more than 1.8 GWh of energy could be saved each year. This is a considerable improvement in the efficiency of the thermal system and would correspond to a 60% reduction in the hotel's area-specific heat consumption.

The specific heat consumption of hotel B in relation to the reference years 2015 and 2016 is shown in Fig. 10. Operational data from 2017 is not included. The system was installed in June 2018 and, similar to hotel A, demonstrated a meager improvement in thermal system efficiency during the first year of operation. However, a reduction of 66.7% in specific heat energy consumption was achieved in 2019, which corresponds to an overall reduction of 73.2 kWh/m²/year or 600 MWh/year in the hotel.

The operation data from hotel A and B demonstrate that CO₂ heat pump systems can achieve a reduction in heat consumption of approximately 60% when compared with EL and DH. However, optimal design of main and secondary systems is essential for a successful implementation of CO₂ heat pumps. The integrated CO₂ unit in hotel B illustrates a sustainable approach to heating and cooling in hotels, as thermal energy is recovered within the building itself and stored for later use. This thermal management philosophy will be essential in the future to reduce energy and power consumption within the hotel sector. The integration of CO₂ technology for heating and cooling in hotels is in its infancy, and the technology must be improved to be acknowledged as a worthy competitor to the traditional HFC systems (Diaby et al., 2019; Byrne et al., 2009). CO₂ refrigeration systems for supermarkets faced similar challenges when the first units were installed in the early 2000s. At present, CO₂ refrigeration is the benchmark solution within the European supermarket sector, where more than 29,000 units are installed (Shecco, 2020). Heat pump and refrigeration systems with low GWP refrigerants are unarguably necessary to reduce global warming and to reach the 2-degree goal of the Paris Agreement (Rogelj et al., 2016). Thus, new areas of application for natural refrigerants must be identified, such as integrated CO₂ heat pumps solution in hotels.

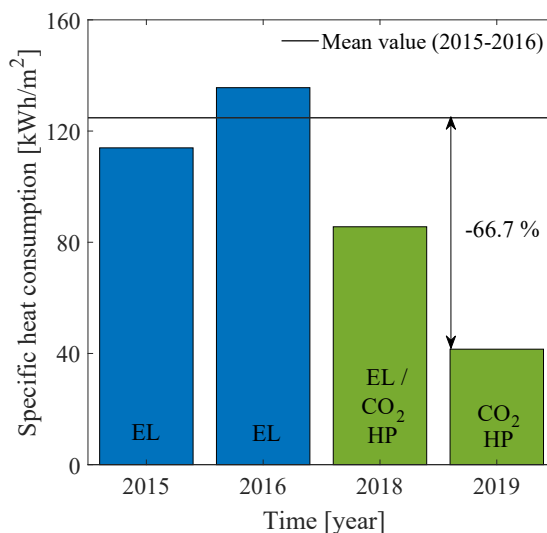


Fig. 10. Heat energy consumption of hotel B for specific years. The reduction in energy usage after retrofit is related to the mean heat energy consumption from 2015 to 2016, as the data from 2017 is insufficient.

4. Conclusions

The energy consumption in cold-climate hotels has been studied for the period 2015–2019 by using field measurements. The following conclusions can be made based on the investigation of 140 hotels in Norway and Sweden.

- 70% of the hotels have a mean annual energy consumption between 150 and 250 kWh/m²/year, with the mean value for all hotels being 213 kWh/m²/year. Thus, there is a potential to further reduce the energy consumption in the hotels.
- A shift towards sustainable energy sources is observed in the sample hotels from 2015 to 2019. Electricity is the most applied energy source in hotels and accounted for more than 70% of the total energy use in 2015. However, the overall electricity consumption was reduced by 8% from 2015 to 2019 in favor of district heating, which increased by 7% over the same period. The access to district heating and cooling increased by 18.0 and 10.9% from 2015 to 2019. The number of hotels with only electricity access has been halved over the five-year period.
- The evaluation of primary and secondary thermal heating systems revealed that 70% of the hotels apply district heating as the main source of heating in 2019. The specific energy consumption for this group of hotels is 219.9 kWh/m²/year, which is larger when compared with hotels that use electricity or heat pump technology to generate heat. The 9% of the hotels that apply heat pumps as their main heating system have the lowest specific energy consumption of all the investigated thermal systems, with 175.4 kWh/m²/year.
- Two of the investigated hotels have been equipped with integrated CO₂ heat pump systems and thermal storage, where a reduction in energy usage in the range of 73.2–88.6 kWh/m²/year was achieved. In both cases, a heat energy consumption reduction of about 60% is observed, revealing the great potential of integrated CO₂ heat pump systems as a thermal solution for hotels.

It can be concluded that heat pump systems, especially the ones relying on CO₂ as the sole working fluid, represent the most

sustainable solution for cold climate hotels, regardless of their size. Therefore, it is thought that highly energy-efficient hotels involving reversible transcritical CO₂ heat pump units and renewable energy technologies will become standard in cold climates in the next few years.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships

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