Energy consumption and demand flexibility potential of residential and service buildings

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Abstract

Due to an increasing integration of renewable energy into energy systems, new flexibility measures are needed to ensure the balance between energy supply and demand. Demand-side management measures, such as demand response (DR) can be used to increase system flexibility. Traditionally, only large industrial consumers have participated in DR. Recently, increased attention has been given to the idea of extending the DR measures to consumers in residential and service sectors. In order to estimate the amount of flexibility available in residential and service buildings, accurate information about their energy consumption and qualitative features is required.

In response to this need, this thesis aims to identify the electrical and thermal loads of residential and service buildings that are best suited for DR. To accomplish this, this thesis will conduct a comprehensive literature review on the energy consumption of both residential and service buildings. Based on the findings of the literature review, a qualitative analysis of the building loads will be carried out. The following factors will be considered in the analysis: energy consumption, timing of consumption relative to peak demand periods, consumer inconvenience and the suitability for an existing DR program.

Keywords demand-side management (DSM), demand response (DR), energy consumption, electricity, heating, residential building, service building

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Tiivistelmä

Uusiutuvan energian käytön lisääntymisen vuoksi energiajärjestelmiin tarvitaan uusia joustotoimenpiteitä energian kysynnän ja tarjonnan tasapainon varmistamiseksi. Energiajärjestelmän joustavuutta voidaan lisätä kulutushallinnan toimenpiteillä, kuten kulutusjoustolla. Perinteisesti ainoastaan suuret teollisuuskuluttajat ovat osallistuneet kulutusjoustoon. Viime aikoina kulutusjoustotoimenpiteiden tarjoamista myös asunto- ja palvelusektorien kuluttajille on alettu tutkimaan. Asuin- ja palvelurakennuksissa käytettävissä olevan joustavuuden arvioimiseksi tarvitaan tarkkaa tietoa näiden rakennusten energiankulutuksesta ja laadullisista ominaisuuksista.

Vastauksena tähän tarpeeseen, tämän diplomityön tavoitteena on kartoittaa kulutusjoustoon parhaiten soveltuvat asuin- ja palvelurakennusten sähkö- ja lämpökuormat. Diplomityössä suoritetaan kattava kirjallisuuskatsaus asuin- ja palvelurakennusten energiankulutuksesta, jonka pohjalta rakennusten sähkö- ja lämpökuormista tehdään laadullinen analyysi. Analyysissa otetaan huomioon seuraavat tekijät: energiankulutus, kulutuksen ajoitus suhteessa huippukysyntätunteihin, kysyntäjouston kuluttajille aiheuttamat haitat ja kuormien soveltuvuus olemassa oleviin kysyntäjousto-ohjelmiin.

Avainsanat kysyntäjousto, energiankulutus, sähkö, lämmitys, asuinrakennus, palvelurakennus

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Contents

Abbreviations

AC	Air Conditioning
CHP	Combined Heat and Power
CPP	Critical Peak Pricing
DEH	Direct Electric Heating
DH	District Heating
DHW	Domestic Hot Water
DLC	Direct Load Control
DR	Demand Response
DSM	Demand Side Management
ED-CPP	Extreme Day CPP
EDP	Extreme Day Pricing
EIA	Energy Information Administration
EU	European Union
EUI	Energy Use Intensity
HDD	Heating Degree Day
HVAC	Heating, Ventilation and Air Conditioning
I/C	Interruptible/Curtailable
ICT	Information and Communications Technology
LDC	Laundry, Dishwashing and Cleaning
OECD	Organisation for Economic Co-operation and Development
PV	Photovoltaics
RTP	Real-Time Pricing
TOU	Time of Use
UAE	United Arab Emirates
UK	United Kingdom
USA	United States of America

1 Introduction

In 2017, the global annual electricity generation reached over 23000 TWh, with solar photovoltaics (PV) and wind power accounting for around 7% [1]. The International Energy Agency (IEA) has estimated that the global renewable power capacity will increase by 50% between 2019 and 2024. The combined share of energy generated by solar PV and onshore wind is projected to represent 85% of this growth. [2] This substantial growth in utilization renewable energy sources is ushered by necessary measures to reduce greenhouse gas emissions and combat global warming [3]. Governments around the world have set goals to reduce the use of fossil fuel use and increase the share of renewables. For example, Finland seeks to achieve carbon neutrality by 2035 [4]. Therefore, large amounts of renewable energy are going be integrated into electrical grids in the future.

However, the integration of large amounts of renewable energy into power systems can be problematic. Variable renewable energy sources, such as solar PV and wind power, have uncertain availability. This uncertain availability is an issue, as power systems must always maintain balance between supply and demand. [5] Therefore, power systems are required to have a certain amount of flexibility, which is the measure of how well the power system can accommodate mismatches between supply and demand [6]. Flexibility is usually accomplished from the supply side using reserve peaking power plants [5],[7]. However, the use of these peaking power plants is expensive, and they are generally less efficient than other power plants [8]. Moreover, peaking plants tend to use fossil fuels, which combined with their lower efficiency, makes peaking plants less environmentally friendly [9].

An alternative method for improving the flexibility of power systems is demand-side management (DSM) [8]. DSM refers to the set of measures that can be undertaken to influence the magnitude and patterns of end-use power consumption [6]. Demand response (DR) is a subset of demand-side management measures, which focus on altering customer energy consumption to better match the energy generation [10]. Traditionally, only large industrial consumers have participated in DR [11]. Recently, increased attention has been given to the idea of extending the DR measures to consumers in residential and service sectors [11],[12].

The current literature on residential and service sector DR focuses largely on estimating the amount of flexibility potential available [13],[14]. These estimations are often made without considering the inconvenience caused by the DR measures to the customers [14]. However, several studies have shown that the inconvenience associated with DR measures may affect the willingness to participate in DR programs [14],[15]. This limits the availability of certain loads for DR measures, which in turn limits the amount of available flexibility [16]. Moreover, flexibility estimations are often based on information about building energy consumption acquired using building-stock models [10],[17],[18]. An increasing number of studies have shown that this method for estimating building energy consumption can be inaccurate [19]-[21].

The aim of this thesis is to evaluate the flexibility potential of building electrical and thermal loads. To accomplish this, this thesis will conduct a comprehensive literature review on the energy consumption of both residential and service buildings. Based on the findings of the literature review, a qualitative analysis of the building loads will be carried out. The following factors will be considered in the analysis: the magnitude of energy consumption, timing of consumption relative to peak demand periods, consumer inconvenience as well as the suitability for an existing DR program. In addition to electrical loads, thermal loads will be taken into account as well, since electricity and heat generation are largely intertwined in systems with large amounts of cogeneration [22]. The analysis of space heating systems will be limited to radiator and floor heating systems, as these tend to be the most common heating systems in northern Europe. Both district heating and direct electric heating systems will be considered.

The rest of the thesis is structured as follows. Chapter 2 gives an overview of the energy consumption of the building sector and reviews the electricity and heating consumptions of different building types. Chapter 3 analyzes the usage pattern characteristics and the consumption shares of different electrical loads. Chapter 4 describes the district heating network and discusses the concept of thermal inertia. Chapter 5 analyzes the usage patterns and the energy consumptions of building thermal loads. Chapter 6 introduces and compares different DR programs and discusses the potential load shaping objectives achieved with DR. In Chapter 7, a qualitative analysis of the flexibility potential of building electrical and thermal loads is performed based on the findings of the literature review. Finally, Chapter 8 concludes the thesis by summarizing the results and suggesting directions for future work.

2 Overview of building energy consumption

The purpose of this chapter is to give an overview of the energy consumption of the building sector. The information laid out in the chapter should give the reader an understanding of the significance of the building sector as it relates to the global energy consumption. First, information about the current status of the building sector and its future trends is presented. Next, in order to highlight some of the issues with predicted energy use and to demonstrate the importance of measured data, the performance gap between the modelled and actual energy consumption of buildings is discussed. Then, definitions of building types are presented. Finally, the magnitudes of energy consumption of different buildings types are outlined and regional and inter-regional differences in energy consumption are discussed.

2.1 Current status and future trends

Globally, the building sector has the second largest final energy consumption. In 2018, residential and non-residential buildings together accounted for 30% of global final energy consumption (Figure 1), or around 105 exajoules (EJ). [23] However, substantial differences in the total final energy consumption of buildings exist between countries and regions, as can be seen from Table 1 [1]. For example, at around 22%, the combined share of residential and non-residential buildings is well below the global average in China. This is largely due to the small share of the commercial and service sector. In India, similarly to China, the commercial and service sector is relatively small. The energy share of India’s residential sector, on the other hand, is significantly above the global average.

It is worth noting that there is some ambiguity in the way statistical data about the final energy consumption is recorded and reported. Consumption is often split into three roughly equally sized categories: industry, transport and “other”. The category “other” is somewhat vague and incorporates different sub-sectors depending on the source. End uses from sectors such as residential, commercial, service, agriculture and forestry and fishing are grouped under “other”. However, recording practices differ between many international, national and regional sources, making comparison between sources difficult. [24],[25]

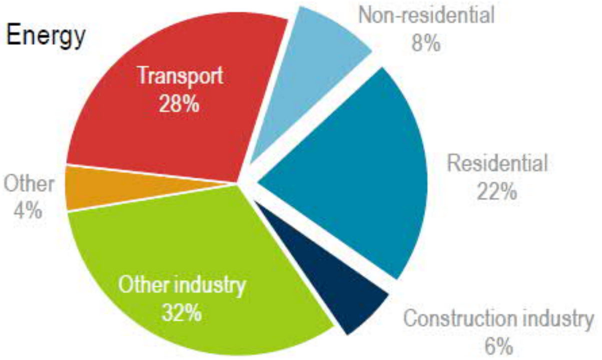

Figure 1: Global final energy consumption by sector [23].

Table 1: Division of total final consumption in selected countries, 2017.

TFC	Industry (%)	Transport (%)	Residential (%)	Non-residential (%)
World	29.0	28.9	21.2	8.1
EU	22.8	28.3	24.6	12.9
USA	17.2	41.1	16.1	13.6
China	49.1	15.5	17.1	4.4
India	34.7	16.6	29.4	4.1
Finland	42.2	16.4	20.5	11.5

From 2010 to 2018, global building final energy consumption increased by 7%, which equal to a growth of over 8 EJ. During same period, electricity use in buildings increased by 19%, or over 6.5 EJ. Energy demand of space cooling increased by 33%, demand of appliances increased by 18% and water heating demand increased by 11%. Changes during the same period in the energy intensity per unit of floor area, which can be used as a proxy for energy efficiency, are shown in Figure 2. [23]

Largest improvements are found in the energy intensity of space heating and lighting, which decreased by 20% and 17%, respectively. Additionally, energy intensity of water heating, cooking and "appliances and other" showed improvements of 10%, 9% and 4%, respectively. On the other hand, the energy intensity of space cooling increased by roughly 8%, which is a result of the fact that an increasingly large proportion of newly built floor area needs to be cooled. This trend is driven by the rapid growth of the floor area in hot countries. From 2010 to 2018, the largest contributors to the growth in building energy demand were increases in floor area and population as well as changes in building use. [23]

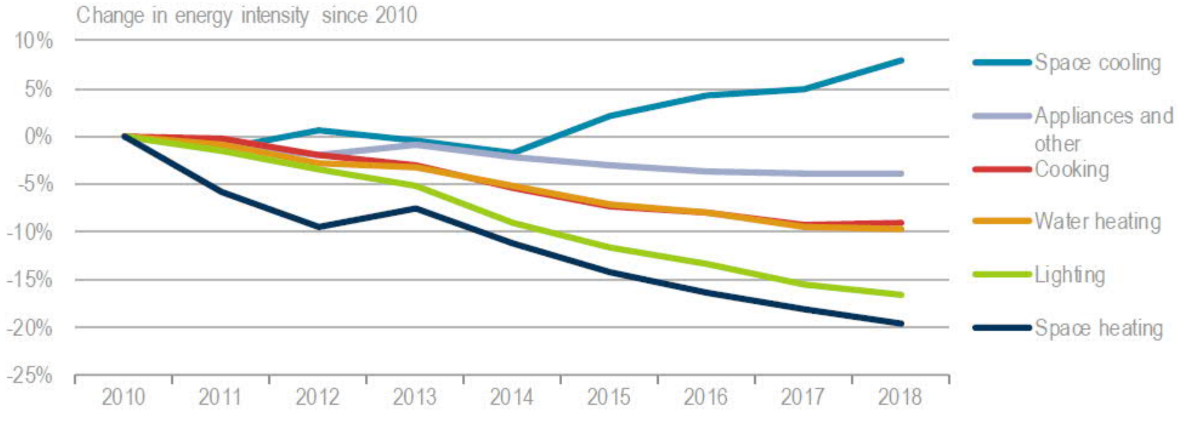

Figure 2: Changes in building sector energy intensity from 2010 to 2018 [23].

From 2018 to 2050, the global total final consumption of residential and non-residential buildings is expected increase substantially [23],[26]. Whereas the residential energy consumption is projected to increase only by 7% in OECD countries, in non-OECD countries it is expected to double. Most of this growth (around 70%) is going to occur in non-OECD Asia, a region that includes China and India. China contributes the most to this growth in absolute terms, while India experiences the fastest relative growth. In addition, during the same period, the residential energy consumption per person increases at a yearly rate of 0.6%. Again, non-OECD countries being the most significant contributor: in OECD countries, residential energy consumption per person decreases by 0.1% per year, while in non-OECD countries it increases by 1.3% per year. [26]

The rate of growth in residential energy use per person is largest in India due to the increased access to energy sources and the increased use of appliances. This growth continues what has been a trend in Indian households since the turn of the 21st century. From 2001 to 2019, the share of households with access to electricity has increased from 56% to almost 100% and the household electricity consumption has tripled. [27],[28] It is worth noting, that in 2050, India's residential energy use per person is expected to be only 24% of that in the United States [26].

From 2018 to 2050, most the growth in commercial and service sectors is expected to happen in non-OECD countries: the non-residential building consumption will increase at three times the rate of OECD countries. However, by 2050, the total final consumption of non-residential buildings is still expected to remain lower in the non-OECD countries than in the OECD countries. Much like in residential consumption, non-OECD Asia is the fastest growing region: consumption increases most in absolute terms in China and India experiences the fastest relative growth. [26]

2.2 Performance gap

In order to properly assess the potential of residential and service buildings as a part of demand-side management, accurate knowledge about their energy consumption is required. Currently, estimations of the flexibility potential of buildings are often based on information regarding the building energy consumption that is acquired by using building-stock models [10],[17],[18]. Stock models are widely popular for estimating the energy consumption of buildings and disaggregating the consumption by different buildings or social categories and end-uses. Different modelling methods include top-down and bottom-up approaches. Whereas top-down modelling works on the aggregated level, bottom-up models are built by combining data of disaggregated components. [29]

However, an increasing body of literature investigating the issues of using stock models shows that this way of estimating building energy consumption can be very inaccurate [19]-[21]. Figure 3 shows the predicted and measured energy intensities of office and educational buildings. These findings were a part of the results of an audit conducted by the UCL Energy Institute in 2013 on the data published on the CarbonBuzz platform[1]. [30] As can be seen, large differences exist between the calculated consumption using the design model and the actual measured consumption. The difference between predicted and actual electricity consumption in educational buildings is as large as 90% (a performance gap of 1.9) [30]. These discrepancies can occur because stock models often fail to account for factors such as socio-technical factors. These models lack the knowledge of how different people consume energy, how they use their household appliances and how they react to energy performance measures. [29]

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[1] CarbonBuzz is a free online tool that can be used to record, track and share information about building energy usage. Available: http://www.carbonbuzz.org/

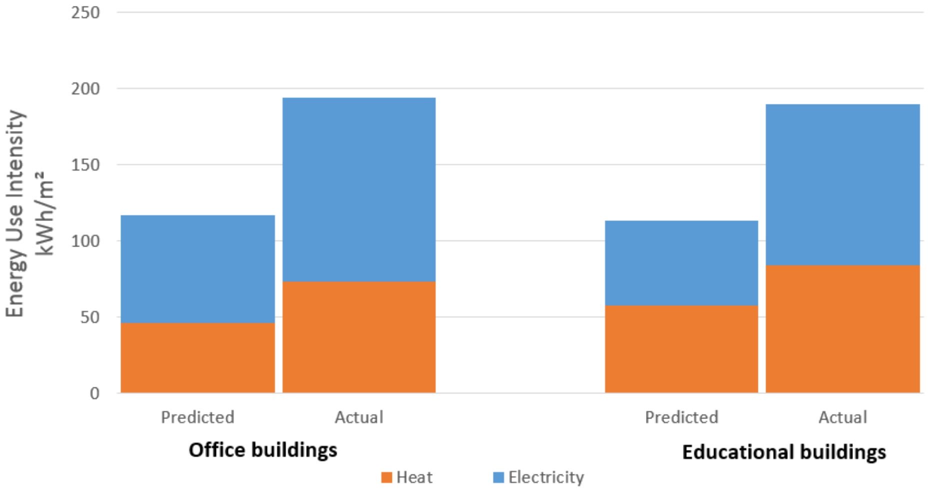

Figure 3: Energy consumption in office and educational buildings – predicted vs. actual.

Various factors influence the accuracy of predictions made using the design model [19],[21]:

- **Model simplifications:** When a real building is transferred into a computer model, simplifications are often necessary for practicality's sake. Such simplifications may include: only estimating the energy use of typical spaces, only reporting the energy used by certain services and assuming that most of the building's systems are off at night.

- **Changes made during design and construction:** The initial design assumption may not accurately reflect what was specified to be built. Additionally, the building may not be constructed as intended. There are many reasons for such disparities: the client's requirements may have changed, the building services may have been altered, the insulation, ventilation, solar and daylight characteristics of the envelope may have changed and the build quality may not have been up to standard.

- **Occupancy, control and management:** The energy performance may further deviate from the initial design after the building has been taken into use. Occupants of the building have a major impact on the energy consumption. The building may not be occupied as expected and, due to the inherit unpredictability, the occupant behavior may differ from initial assumptions. In addition, the maintenance and energy management may not be up to standard. Indeed, the control strategy is often responsible for unexpectedly large energy consumption as the building's systems and equipment may be unnecessarily on by default.

2.3 Building types

Whereas the term "residential building" is mostly straightforward and universal, there is a fair amount of ambiguity regarding the term "service building". For example, the

U.S. Department of Commerce includes buildings such as offices and medical buildings under commercial buildings [24]. On the other hand, Statistics Finland lists medical buildings under “buildings for institutional care” and warehouses as their own category [31]. Because of this, the term “service building” will be used in this thesis from here on out to encompass all public and private buildings that offer services, including buildings often referred to as “commercial buildings”. A more detailed classification, based on the classifications of Statistics Finland, is shown in Figure 4.

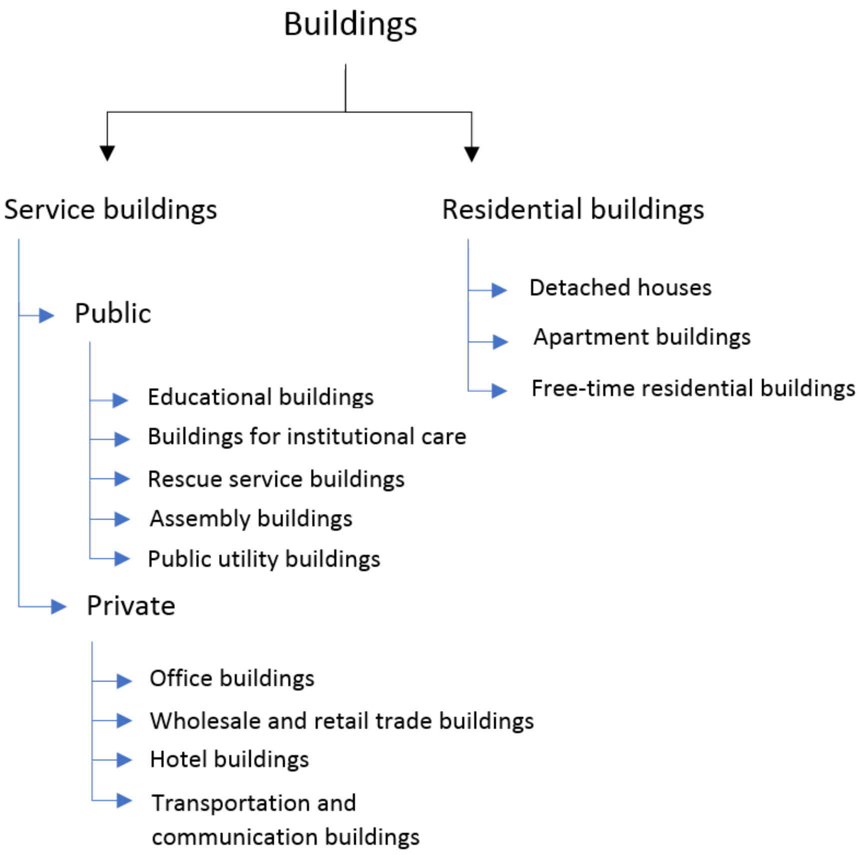

Figure 4: Classification of residential and service buildings.

According to Statistics Finland, residential buildings are defined as buildings intended for continuous living use where the living space constitutes at least half of the total floor area. Residential buildings consist of one or more dwelling units, rooms or other space used by residents, such as storage. Residential buildings include apartment buildings, detached houses and free-time residential buildings, like summer cottages. [31] A household refers to a house or apartment and the people who live there.

Even though there is no clear definition of what constitutes as a service building, the definition given in Figure 4 includes majority of the important building types that contribute significantly to total energy consumption of the building sector. These buildings include buildings that may be classified as “service” or “commercial” in the literature. Short descriptions of public and private service building types are given below [31].

Public service buildings:

- **Educational buildings:** Buildings intended for childhood education, teaching and scientific research, such as elementary schools, upper secondary schools and university and research institute buildings.

- **Buildings for institutional care:** Buildings intended for providing human and animal health care, social work activities and correctional treatment, including central hospitals, laboratory buildings, rehabilitation centers and prisons.

- **Rescue service buildings:** Fire stations, civil defense shelters and emergency response centers.

- **Assembly buildings***:* Buildings that are used for arranging performances, exhibitions and competitions. Included here are cultural buildings, such as theatres, museums and libraries, buildings for sports and physical activities and buildings of religious communities.

- **Public utility buildings:** Water supply, sewerage and waste management buildings and material recycling buildings.

Private service buildings:

- **Office buildings:** Buildings intended for performing work such as financial and insurance activities, legal and accounting activities, advertising and marketing, data processing and other information service activities.

- **Wholesale and retail trade buildings:** Commercial buildings intended for the sale of products and services. For example, shopping halls, shopping centers and department stores.

- **Hotel buildings***:* Commercial buildings that are primarily intended for short-term accommodation, including hotels and similar accommodation buildings and holiday buildings.

- **Transport and communication buildings:** Buildings used by the transport and communication industry, such as station buildings, vehicle depots, car parks, data centers and telecommunication stations.

2.4 Energy consumption by building type

In this section, literature on electricity and heating consumption of residential and service buildings is reviewed. Service buildings discussed here are limited to hospitals, offices, hotels, wholesale and retail trade buildings and educational buildings. These buildings were selected as they are among the most widely studied buildings types and likely most significant in terms of energy consumption.

As will be seen in the next subsections, service buildings are a much more heterogeneous group in terms of energy consumption than residential buildings. This is because different types of service buildings, unlike residential buildings, have distinctly different uses. Moreover, since service buildings encompass many different building types, there is a lot more variation in building sizes and consumption patterns compared to residential buildings. All the following factors affect the energy consumption of a service building: floor area, amount of building area cooled and heated, worker density, personal computer density, extent of food services and training facilities and weekly open hours [32]. While these factors obviously differ greatly between building types, significant differences exist between buildings of the same type as well.

Energy use intensity (EUI) will be used when comparing the energy consumption buildings of different sizes. This is done to normalize the energy consumption in terms of building floor area. EUI represents the energy performance of a building, and it is defined as the annual total energy consumption divided by the floor area [33].

2.4.1 Residential buildings

The annual electricity consumption per household in the EU are shown in Figure 5. The EU average electricity consumption in 2017 was roughly 4000 kWh per household. However, as is evident from Figure 5, there are large discrepancies between countries: average household consumption in Romania is around 1600 kWh, compared to 8000 – 10000 kWh in Finland and Sweden, and over 17000 kWh in Norway. Electricity consumption is affected the most by differences in the use of electrical heating, levels of appliance ownership and energy efficiency [34],[35].

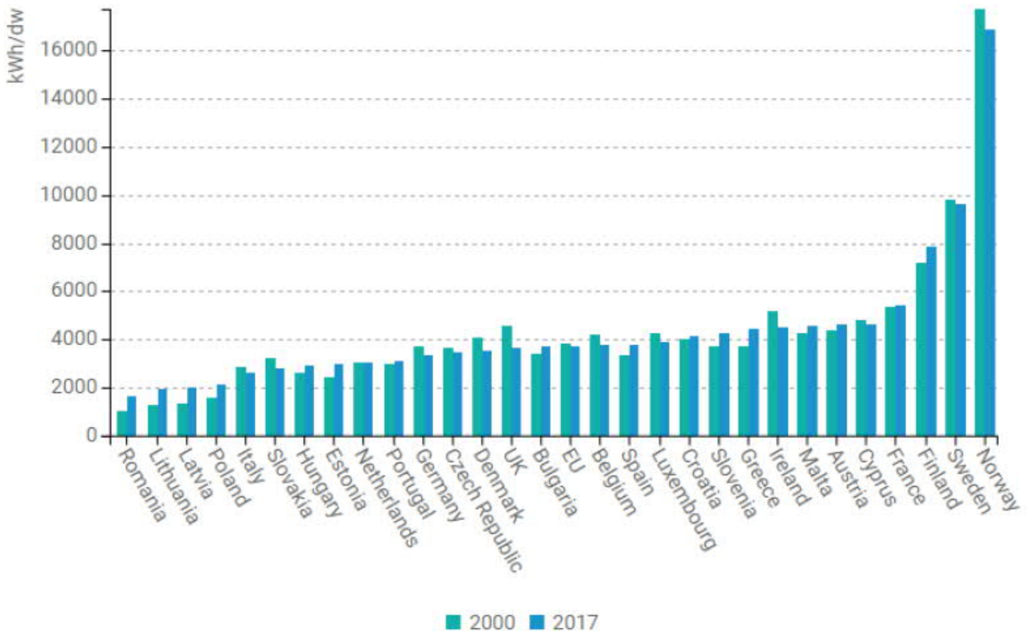

Figure 5: Annual electricity consumption per dwelling in the EU [34].

Additionally, inter-regional differences can be significant. Figure 6 shows the distribution of 250 UK households without electrical heating by electricity EUI [36]. The difference in consumption between the least consuming and the most consuming households can be an order of magnitude. Table 2 shows the average annual household electricity consumption by household type. On square meter of floor space area basis, different types of households had similar consumptions, except for multiple person households with no dependent children. Single-person households had the highest per-person consumption at 2015 kWh. As expected, the households with children had the lowest per-person consumption at 866 kWh. It is interesting to note that households with children had a lower average absolute per-household consumption than single-person households.

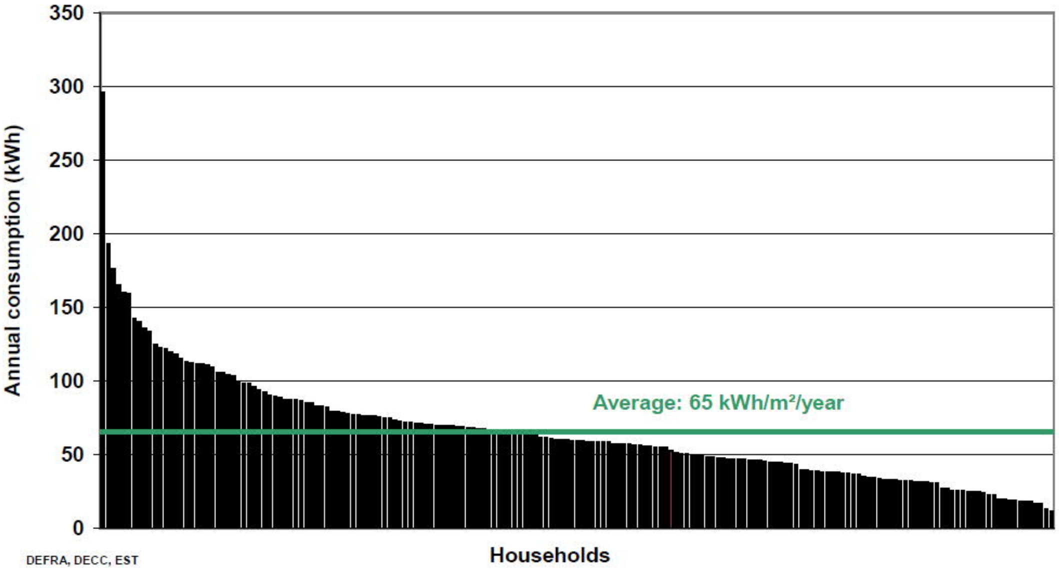

Figure 6: Distribution of annual household electricity consumptions per m^2 [36].

Table 2: Average annual household electricity consumption by household type.

Household type	**Annual consumption (kWh)**		
	Per household	Per m^2	Per person
All households	3638	65	2012
Single non-pensioner household	3562	62	3562
Household with children	3244	62	866
Multiple person household with no dependent children	4194	73	1870

In 2017, the EU average annual heating consumption was around 0.9 toe (tons of oil equivalent), or roughly 10500 kWh, per household (Figure 7). Again, large differences in consumption exist between countries. Malta, Portugal and Cyprus have the lowest average annual consumption at under 0.1, around 0.15 and around 0.3 toe per household, respectively. On the other hand, the average annual household heating consumption in Luxemburg is close to 1.9 toe. [34] Regional differences in household heat consumption are mostly due to the climate and household floor space area, warmer climate and less floor space being associated with lower average household consumption [34],[37]. Household heating consumption in terms of EUI is shown in Figure 8. In 2017, the EU average household heating EUI was around 115 kWh/m^2, down from around 170 kWh/m^2 in 2000.

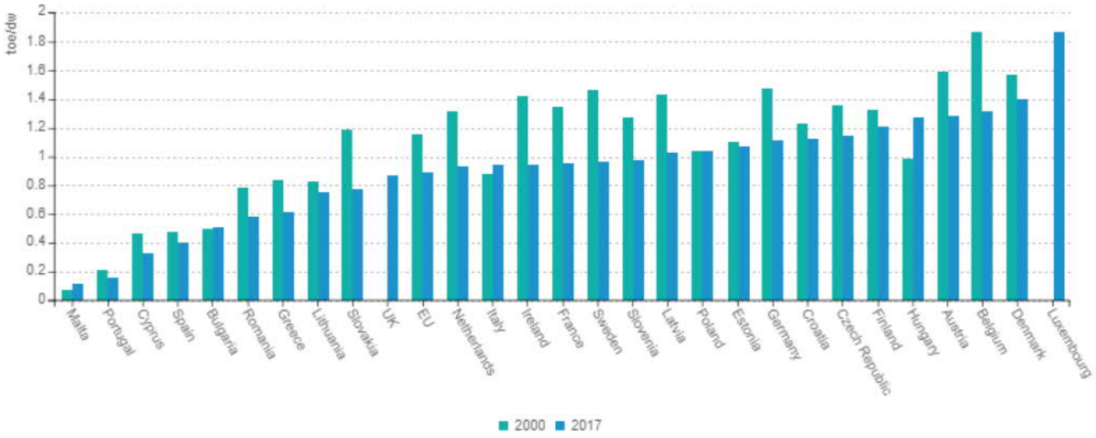

Figure 7: Annual household heating consumption per dwelling in the EU [34].

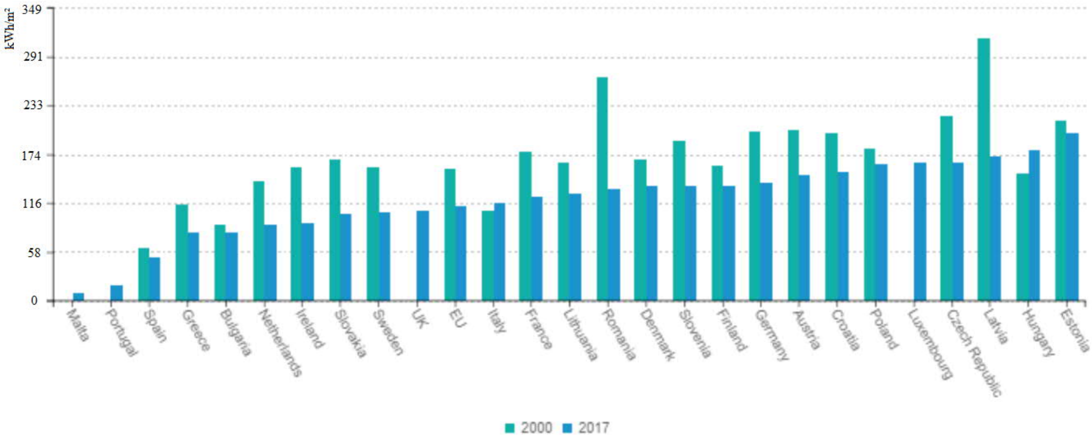

Figure 8: Annual household heating EUI in the EU. Edited from [34].

Figure 9 shows the heating energy use intensity of residential buildings in five different cities in China. The five cities are in three different climate regions classified as “severe cold climate zones” A, B and C. The average outdoor temperature is the lowest in climate zone A and highest in C, with average temperature in climate zone B being between the two. Baotou, Hohhot and Tuquan are located in zone C, Xilinhaote is located in zone B and Hailar is located in zone A. Significant inter-regional differences in heating energy use intensity can be seen: the variation can be up to 1500 kWh/m^2. [38] Although the heating consumption tended to be larger in colder regions, the within-region variation was so significant that outdoor temperature alone cannot accurately predict a building’s heating consumption. This is further confirmed by the fact that the average heating consumption of Xilianhaote was greater than that of Hailar, even though Hailar is in a colder climate region. It is worth noting that values of the heating

EUIs shown in Figure 9 are significantly higher than the values of the EU households shown in Figure 8. This is likely due to differences in building physical characteristics, such as the level of insulation, between the regions.

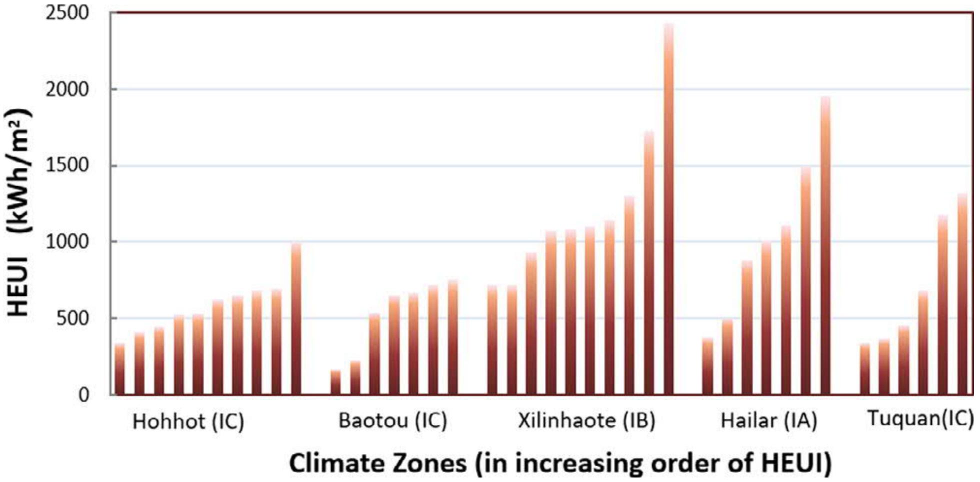

Figure 9: Annual heating energy use intensity of building in three different climate regions [38].

The indoor thermal environment and the heating system operation level can have a notable impact on a building's heating consumption [38]. The indoor temperature is partially controlled by the occupant's thermal comfort preferences and behavior. This is particularly significant for newer buildings. Newer, more energy efficient buildings have a larger portion of the variation in heating consumption in explained by occupant behavior, compared to older buildings. In older buildings, the physical characteristics tended to be most important for explaining variance in heating consumption. This can be seen from Figure 10. [39] For buildings built after 2006, around 55% of the variation was explained by user behavior (abbreviations SO and NO) and around 45% by building characteristics (abbreviations Ph and AB). For buildings built before 1938, the numbers were 50% and 49% for occupants and building characteristics, respectively.

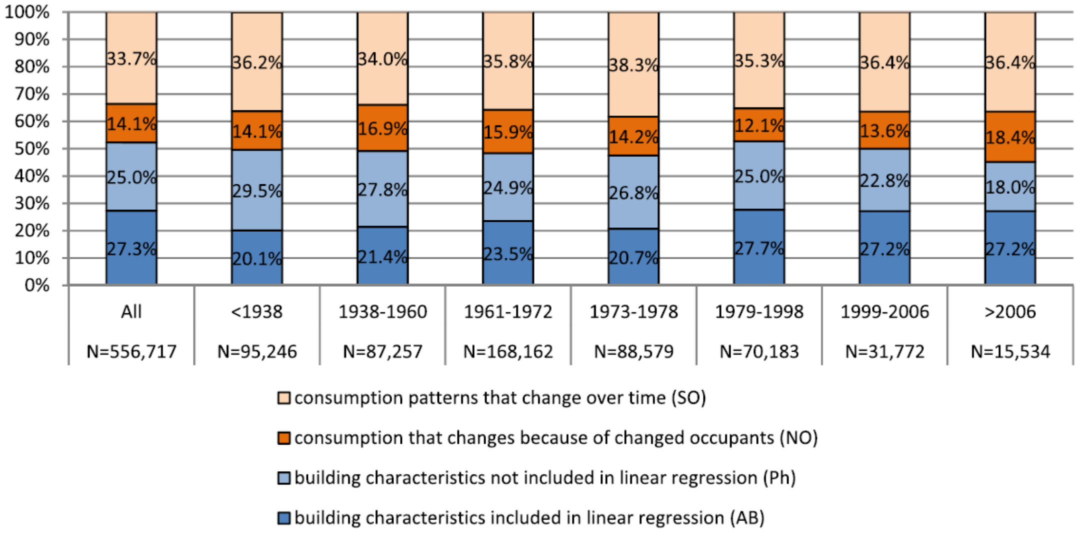

Figure 10: Influence of occupants and building characteristics on variance of heating consumption [39].

2.4.2 Hospital buildings

Table 3 shows the energy use intensities of hospital buildings. Hospitals are one of the most energy intensive service buildings due to the high space heating, cooling and ventilation loads as well as high number of medical equipment. In addition, majority of the facilities are in constant operation, leading to a continuous energy usage pattern [40],[41]. Hospitals for five different U.S. climate zones, varying in temperature from "very cold" to "very hot", are listed in descending order. Likewise, hospitals for four different Chinese climate zones, varying in temperature from "frozen" to "hot summer & warm winter", are listed in descending order. In the case of the U.S. hospitals, the total energy intensity consistently decreases going from "very cold" to "very hot". This is because while the electricity use intensity is relatively similar between the different climate zones, the heating intensity decreases as the climate gets warmer. In China, this trend is reversed. Hospitals in the colder climate zones have a lower total EUI compared to the hospitals in the warmer climate zones. The electricity EUI increases over three-fold going from "frozen" to "hot summer & warm winter" due to the increased use of air conditioning [40]. Interestingly, heating EUI is also larger in the warmer climate zones than in the colder climate zones. In China, the larger electricity and heating consumption associated with warmer climates is likely explained by the larger portion of more specialized hospitals with greater energy use intensity in the warmer climate zones [40].

Table 3: Hospital building energy use intensity by region.

Country	**Reference**	**Energy use intensity (kWh/m^2 a)**		
		Electricity	Heat	Total
USA	[41]	300.3	399.7	700
USA	[41]	279.9	359	638.9
USA	[41]	354.1	405.7	759.8
USA	[41]	339.1	355.2	694.3
USA	[41]	305.7	261.5	567.2
China	[40]	45.2	233.6	278.8
China	[40]	69.4	231.1	300.5
China	[40]	104.8	274.8	379.6
China	[40]	140.7	273.9	414.6
Singapore	[42]	345	-	-
Malaysia	[43]	234	-	-
Thailand	[44]	148.8	-	-
South Korea	[45]	120	453	573
Germany	[46]	-	-	270
Spain	[47]	-	-	270

2.4.3 Office buildings

Table 4 shows the energy use intensities of office buildings by region. Regional differences in the energy use intensities of office buildings are relatively small. Inter-regional differences are mostly due to differences in air conditioning. Office buildings with air conditioning consume twice as much electricity per floor area unit than offices with no air conditioning. This can be observed from the listed UK office building: electricity EUIs of air conditioned and non-air conditioned offices are 219 kWh/m^2 and 108 kWh/m^2 per year, respectively [48].

Like in residential buildings, occupant behavior is a significant factor affecting the energy consumption in office buildings. Electricity consumption in office buildings is largely caused by the operation of appliances and equipment that is controlled by the occupants. The way the occupants interact with the electrical appliances can have a significant impact on the total energy consumption. [49] Choices, such as whether to leave personal computers or lights on when leaving the workstation, can have a meaningful impact on the energy consumption in the long run. Although occupant behavior affects the energy consumption in most building types, its effect in offices is particularly significant [50]. This is likely because the occupants have larger degree of control over the thermal environment and illuminance levels in offices, compared to other service buildings [50],[51].

Table 4: Office building energy use intensity by region.

Country	**Reference**	**Energy use intensity (kWh/m^2 a)**		
		Electricity	Heat	Total
Singapore	[42]	212	-	-
South Korea	[45]	149	93	242
China	[52]	126	-	-
China	[53]	292	-	-
UK	[48]	219	107	326
UK	[48]	108	85	193

2.4.4 Hotel buildings

Energy use intensities for hotel buildings are listed in Table 5. For hotel buildings, the main cause of EUI differences is the level of sophistication, or the star-rating, of the hotel. This trend is illustrated in Table 5. For EU, hotels of two different grades are listed: mid-market hotels and upscale hotels. The upscale hotels had a considerably higher average annual energy use intensity of 364.3 kWh/m^2 compared to the 285 kWh/m^2 of the mid-market hotels. This trend is even more pronounced in Chinese hotels. Hotels with a star-rating of one through four are listed in descending order. The difference in EUI between a one-star and a four-star hotel is almost three-fold. The greater energy intensity of the higher grade hotels is mainly explained by the types of service offered and technical installations in the buildings [33],[54]. For example, none of the Chinese one-star hotels had an air conditioning systems installed, whereas the prevalence of air conditioning was 64% in four-star hotels [33]. Moreover, the more upscale brand hotels are often equipped with other energy intensive facilities and systems, such as health clubs, spa and pools, jacuzzies and on-site laundries [54]. Noteworthily, [54] concluded that even though varying climate conditions due to seasonal changes affected the energy consumption of individual hotels, clear differences in consumption between hotels located in different climate zones could not be observed.

Table 5: Hotel building energy use intensity by region.

Country	**Reference**	**Energy use intensity (kWh/m^2 a)**		
		Electricity	Heat	Total
EU[2]	[54]	137.7	147.3	285
EU[3]	[54]	179.6	184.7	364.3
Greece	[55]	393.2	17.1	410.3
China	[33]	-	-	70.2
China	[33]	-	-	74.2
China	[33]	-	-	113.3
China	[33]	-	-	180.8
Singapore	[42]	267	-	-
Singapore	[56]	361	66	427
South Korea	[45]	223	607.2	830.3

2.4.5 Wholesale and retail trade buildings

Wholesale and retail trade buildings are a diverse group of service buildings, ranging from small convenience stores to large shopping centers. Table 6 shows the energy use intensity of wholesale and retail trade buildings, including shopping centers and food retail stores, such as convenience stores, supermarkets and hypermarkets. Of all the service building types examined here, shopping centers and food retail stores are by far the most electricity intensive buildings. For these types of service buildings, shopping centers in particular, the regional differences in energy consumption are substantial: the difference in consumption between a shopping center in the United Arab Emirates and a shopping center in China can be ten-fold. These differences are likely explained by the level of sophistication, types of services provided and prevalence of air conditioning.

The energy use intensity of shopping centers and food retail stores is largely dictated by the sales floor area [57],[58]. Particularly in food retail, as the floor area decreases, the EUI of the building increases exponentially, as is shown in Figure 11. This is because as the floor area increases, the emphasis of the sales operations shifts from food-dominant to non-food dominant. In terms of EUI, this shift is significant because refrigeration systems are the largest energy consumer in food retail stores. [58]

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[2] Measurements taken from hotels of the *Scandic Hotels* chain in the geographical zone of 9°W–35°E, and 70°N–35°S.

[3] Measurements taken from hotels of the *Hilton Hotels & Resorts* chain in the geographical zone of 9°W–35°E, and 70°N–35°S.

Table 6: Wholesale and retail trade building energy use intensity by region.

Country	**Reference**	**Energy use intensity (kWh/m² a)** Electricity	Heat	Total
UAE[4]	[57]	2467	-	-
UAE[5]	[57]	538	-	-
UK	[59]	1117.3	-	-
UK[6]	[58]	1480	-	-
UK[7]	[58]	770	-	-
UK[7]	[60]	875	470	1345
UK[8]	[60]	610	200	810
Singapore	[42]	366	-	-
China	[61]	239.8	-	-

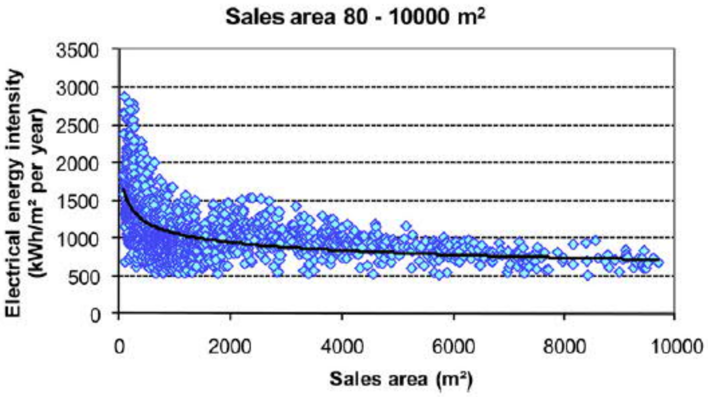

Figure 11: EUI as a function of sales floor area in UK food retail stores [58].

2.4.6 Educational buildings

Educational buildings include buildings intended for childhood education, teaching and scientific research. EUIs of different educational buildings are shown in Table 7. Out of the examined service buildings, educational buildings have the lowest average energy use intensity. Their electricity and heating consumptions can as low as in residential buildings (Table 2, Figure 8). Electricity consumption of educational buildings is largely associated with the level of education provided. University buildings have a higher EUI than day care centers and schools due to the larger number of specialized equipment and spaces, such as laboratories and lecture halls [62]. Similarly, secondary schools tend to consume more electricity than primary schools, likely due to the more widespread use of electric appliances for ICT purposes [63].

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[4] Shopping center located in Ajman with an enclosed CFA of 6044 m^2.

[5] Shopping center located in Dubai with an enclosed CFA of 87831 m^2.

[6] Convenience stores with a sales floor area of 80 – 280 m^2.

[7] Supermarkets with a sales floor area of 280 – 1400 m^2.

[8] Hypermarkets with a sales floor area of >5750 m^2.

Moreover, large differences were found between educational buildings of the same type, as shown in Table 7 [62]. However, for most day care centers, schools and university buildings, electricity consumptions were between 50 and 100 kWh/m^2 and heating consumptions between 100 and 200 kWh/m^2. Heating consumption was shown to be lower for newer educational buildings, whereas primary electricity consumption trended upwards for newer day care centers and school buildings. [62]

Table 7: Educational building energy use intensity by region.

Country	**Reference**	**Energy use intensity (kWh/m^2 a)**		
		Electricity	Heat	Total
Finland[9]	[62]	37-372	61-551	-
Finland[10]	[62]	10-125	45-383	-
Finland[11]	[62]	89-450	6-178	-
UK	[64]	67	49	116
UK	[64]	233	32	265
UK	[63]	43	122	165
Greece	[65]	9	79	88

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[9] Day care centers with floor area of 342 – 1853 m^2.

[10] Schools with floor area of 1012 – 13520 m^2.

[11] University buildings with floor area of 1479 – 41419 m^2.

3 Electrical loads

This chapter focuses on loads within residential and service buildings that consume electrical energy. The electricity consumption patterns of residential and service buildings are complex and affected by multitude of different factors. These factors include: the types and numbers of electrical equipment and appliances, user behavior and their use the equipment, occupancy profile of the building and energy management technologies installed in the building. Additionally, in the case of service buildings, there may be energy management policies and regulations made by the organization. [49],[55] Therefore, in order to accurately estimate the flexibility of electrical loads, they must be accurately described. The purpose of this chapter is to:

- Present and define the systems and appliances most significant in terms of magnitude of electricity consumption and peak power demand
- Describe the characteristics and consumption patterns of those systems and the factors affecting the consumption.
- Discern if some specific electrical loads are particularly significant contributors to the consumption of certain building types.

Each section of this chapter focuses on a different type of electrical load or system. The building electrical loads and systems are presented in the following order:

1. Air conditioning
2. Lighting
3. Cold appliances
4. Active appliances
5. Continuous and standby appliances

3.1 Air conditioning

Air conditioning (AC) is term that refers to a system providing improved indoor air quality and thermal comfort. The term is often used interchangeably with HVAC (heating, ventilation and air conditioning) in the literature. AC systems vary in terms of size from small devices designed for cooling a single room to large systems for entire buildings or large building premises, such as office complexes. Although most of the air conditioning systems are powered by electricity, some large systems use natural gas, excess heat or direct solar energy. These types of AC systems are called thermally driven chillers which are mostly used in the service sector. Another less common form of air conditioning is evaporation cooling, which works by evaporating water using the thermal energy in the air. Due to its working mechanism, evaporative cooling requires a hot and dry climate. By far the most common type of AC system is a vapor compression refrigeration cycle system that is powered by electricity. In 2016, electricity accounted for just under 99% of the energy used for AC. [66]

Air conditioners are mostly used for space cooling, though they can be used for heating purposes as well. For example, residential and service buildings that are outside of the area covered by a central heating network can be heated using ACs [67],[68]. As a result, there are some differences in recording practices between sources. Most authorities, such as IEA and EIA, record the energy consumption of air conditioning under space cooling [26],[66]. On the other hand, Statistics Finland records the electricity consumption of ACs under electrical space heating [69].

3.1.1 Electricity consumption

The growth of energy use of space cooling is shown in Figure 12. The share space cooling of the total energy use in buildings has more than doubled in just over 25 years from under 3% in 1990 to about 6% in 2016. In 2016, the total electricity consumption for cooling was 2000 TWh, which accounted for nearly 10% of that year's global total electricity consumption. It should be noted that within Figure 12, cooling includes AC, dehumidifiers and fans, though globally, most of the energy is used by ACs. [66]

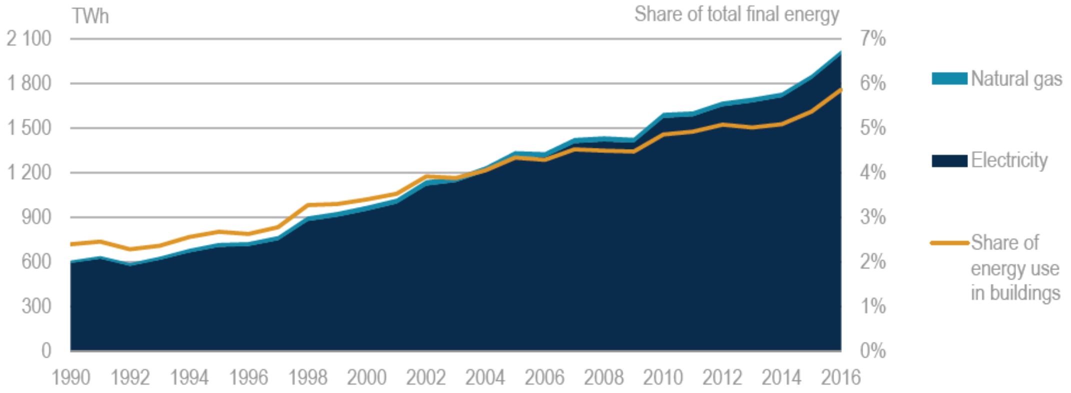


Figure 12: Global space cooling consumption in buildings [66].

At around 6%, the share of air conditioning of the global total building energy consumption is low. However, due to the massive disparities in access to space cooling around the world, there are large regional differences in energy consumed by ACs [66]. In regions where the use of air conditioning is more common, its share of building energy consumption is significant.

Table 8: Installed capacity and annual sales of AC units by region, 2016.

Region	**Output Capacity (GW)**					
	Installed capacity			Annual sales (2016)		
	Residential	Service	Total	Residential	Service	Total
World	6181	5491	11673	848	359	1207
USA	2295	2430	4726	314	129	443
EU	195	654	847	34	41	75
China	2092	807	2899	305	81	386
Japan	407	352	759	47	14	61
India	77	72	149	14	12	25

Regional differences in installed cooling output capacity can be seen from Table 8 [66]. In USA and Japan, the installed capacity is similar between residential and service sectors. In the EU, air conditioning is mostly used in the service sector. In most European countries, the use of residential air conditioning is negligible. For example, in northern Europe, very few households have air conditioning. In Germany and France, the portion of households with an AC are 3% and 5%, respectively.

Table 9 shows the electricity consumption share of AC in residential and service buildings. As shown in Table 9, AC can account for as much as half of the electricity consumed by hospitals, offices and wholesale and trade buildings. In hotel and lodging buildings, AC consumes just under one third of the total electricity. The massive regional differences in household AC use are reflected in Table 9: the share of AC of the total electricity consumption can vary from 1% in UK households to 17% in US households. In Italian and Greek households, AC accounted for an average 3% of the total electricity consumption. However, it is worth noting that the data for the AC usage in UK, Italy and Greece was based on very few monitored appliances. For UK, out of the 251 monitored households, only one AC unit was found available for monitoring [36]. For Italy and Greece, 13 AC appliances were found out of the 183 monitored households [70].

Table 9: Electricity consumption of AC by building type.

Building type	**Reference**	**Share (%)**
Residential	[36],[69],[70]	1 - 17
Hospital	[40],[41],[46]	50 - 57
Office	[52],[71],[72]	42 - 57
Hotel	[73],[74]	28 - 32
Wholesale and retail trade	[58],[61],[75]	9 - 50
Educational	[74]	15

3.1.2 Peak demand and effects of weather conditions

Air conditioning can account for a disproportionately large share of peak electricity demand. Because cooling demand is largely dependent on weather conditions, it typically increases drastically during periods of extreme heat. For example, in the US, space cooling can represent as much as 70% of peak residential electricity demand during heatwaves. Moreover, in countries where space cooling is needed throughout the year, the share of air conditioning of the total peak load can be over 50%. Even in regions and countries with less overall space cooling use, heatwaves can substantially increase peak demand: in France a heatwave increased the peak power demand in August 2003 by 4000 MW, or around 10%. The share of space cooling of the total and peak electricity demand is shown in Figure 13. As can be seen, it is not uncommon for space cooling to account for almost twice as much of peak demand as of total demand. [66]

The effect of temperature on the cooling demand is relatively higher in OECD countries compared to non-OECD countries. The per capita cooling electricity response in non-OECD cities ranges from 0 to 13 watts per degree, whereas in OECD cities it ranged from 15 to 151 watts per degree [76]. However, in most non-OECD countries, the effect of temperature on electricity demand is increasing rapidly. Figure 14 shows the evolution of cooling response to temperature in Dakar from 2012 to 2014 [76]. The cooling response significantly increased during the reviewed period. This suggests that in the future, air conditioning will have even larger impact on the peak electricity demand, especially in countries where there is potential for wider adoption of space cooling.

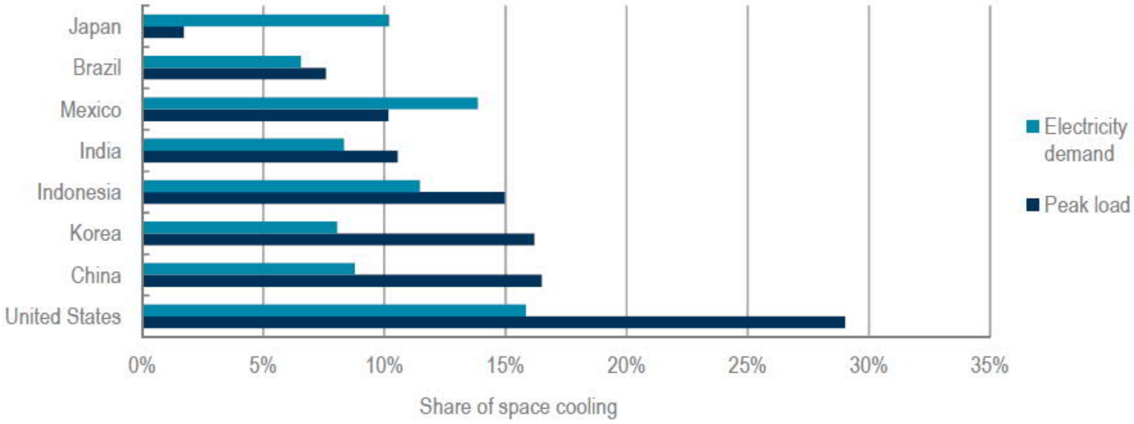


Figure 13: Share of space cooling in total and peak electricity demand, 2016 [66].

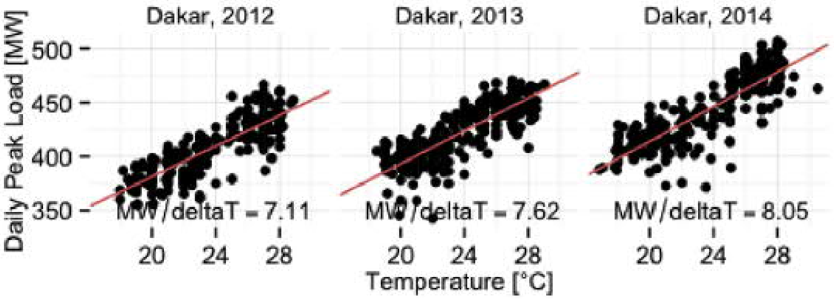


Figure 14: Observed growth in cooling electricity response in Dakar [76].

3.1.3 Time of use and effects of occupancy

The daily electricity consumption profile of an office building air conditioning system is shown in Figure 15 [77]. Energy consumption associated with AC occurs mostly during the hours the building is occupied. After 6 AM there is a steep increase in consumption as the workers arrive at the office. Consumption quickly levels off and stays relatively same until 6 PM, after which the workers leave, and the consumption quickly decreases. This trend repeats not only on workdays, but on weekends as well, though the magnitude of the consumption is much lower on weekends, as less people are in the building. [49],[77] Occupancy has a similar effect on consumption in residential buildings, where AC is mostly only used when the occupant is home [36],[67].

The aforementioned trend does not hold true for all building types. For example, the electricity consumption of hotel buildings is not well correlated with occupancy [78]. Air conditioning in particular was widely used continuously in guest rooms and other areas, regardless of occupancy [55],[78]. Similar trends were found in shopping centers and supermarkets, where the air conditioning was still operating with few or no occupants [61],[79]. In supermarkets, air conditioning is used during the store's open hours, regardless of occupancy profile of the building [79]. This is likely caused in part by oversized air conditioning systems: [79] noted that the air conditioning systems are often purposely oversized with the degree of oversizing ranging from 30% to 200%.

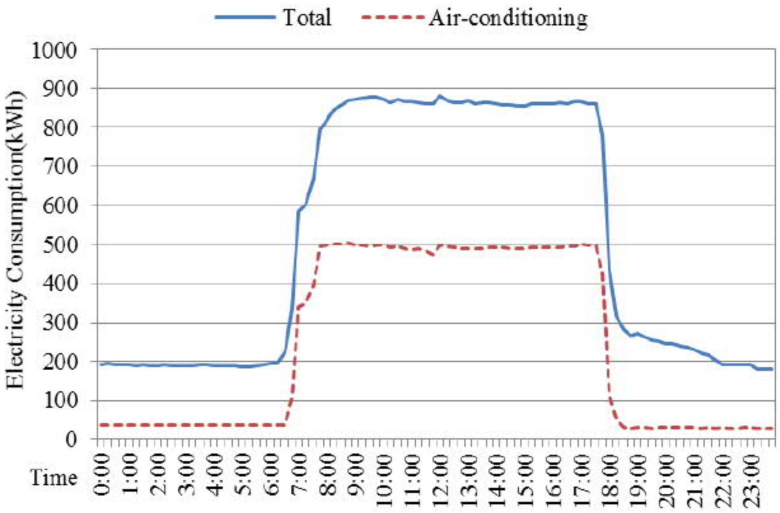


Figure 15: Daily total and air conditioning electricity consumption of an office building [77].

3.2 Lighting

A lighting system consists of lamps, luminaries and the control gear. Lamps account for most of the energy consumed by the lighting system, though control equipment, such as electrical ballasts do contribute as well. [80] A building's lighting system consists of the lighting units inside of the building as well as any outdoor lighting on the property of the building [81]. In residential buildings, outdoor lighting accounts for around 20% of the electricity consumed by lighting [17]. Only the consumption of grid connected lighting systems of buildings is considered in this thesis. Furthermore, the analysis is limited to lighting systems used for illuminance, since not much information is available about the consumption of advertisement lighting systems. Lighting systems are assumed to consume only electricity, as the share of other fuels is negligible.

3.2.1 Electricity consumption

Energy consumed by electrical lighting accounts for between 17% and 20% of the global electricity consumption. Buildings account for around 73% of the global lighting electricity consumption, with residential buildings and service buildings accounting for 28% and 48%, respectively (Figure 16). [82] It is likely that the global electricity consumption of lighting is going decrease in the future. This is due the gradual phase-out of energy-inefficient lighting technologies, such as incandescent lamps. Light emitting diodes and compact fluorescent lamps can consume up to 85% less electricity than incandescent lamps. Significant energy savings may be realized as the transition to these more energy-efficient lamps continues. [83]

Table 10 shows the share of lighting of the building total electricity consumption in residential and service buildings. For residential buildings in most European countries, lighting tends consume between than 10% and 20% of the total electricity. However, in less developed countries, such as some of the newer EU countries, the share of lighting is more significant. For example, in Romania, lighting accounts for over 35% of household total electricity consumption [84]. In hotel buildings, electricity consumption of lighting is proportionally similar to residential buildings.

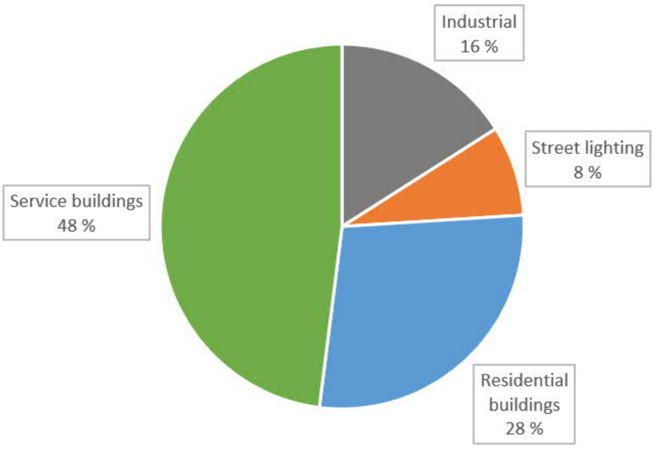


Figure 16: Division of global lighting electricity consumption.

In hospital buildings, lighting accounts for between 16% and 40% of the total electricity consumption. This wide range is most likely explained by the different levels of specialized care offered by the hospitals [41],[85]. In hospitals with large amounts of specialized equipment, medical equipment accounts for larger percentage of the total electricity consumption, thus lowering the share of lighting. In wholesale and retail trade buildings, lighting is a major consumer of electricity. The share of electricity consumed by lighting depends on the size, format and opening hours of the store [58],[60]. In stores where less floor space area is dedicated to refrigerated goods, lighting accounts for a larger portion of the total electricity consumption [58]. In office buildings, lighting represents the second largest end-use of electricity, after AC.

Table 10: Electricity consumption of lighting by building type.

Building type	**Reference**	**Share (%)**
Residential	[36],[70],[84]	10 - 20
Hospital	[41],[43],[85],[86]	16 - 40
Office	[53],[72]	19 - 29
Hotel	[73],[74]	12 - 13
Wholesale and retail trade	[58],[60],[87]	12 - 30
Educational	[74]	17

3.2.2 Effects of occupancy and external illuminance

The daily lighting electricity consumption of an office building is shown in Figure 17 [88]. Similarly to air conditioning, the consumption pattern of lighting corresponds with the arrival and departure of workers: lights are turned on when the workers arrive and turned off when they leave at the end of the workday [88],[89]. Additionally, a reduction in consumption can be observed in the middle of the workday, corresponding with lunchtime [89]. This indicates that lights are less likely to be left on in a non-occupied room compared to air conditioning, where such trend could not be observed (Figure 15).

On the other hand, weather conditions have less of an impact on the electricity consumption of lighting than on the consumption of AC appliances. In particular, the level of external illuminance seems to have no effect on the usage of indoor lights [88]-[90]. This suggests that occupants tend to turn on the lights and leave them on for as long as they are in the office, regardless of the outdoor illuminance levels [65]. This is particularly significant as the illuminance levels of worker desktops can be high even with no internal lighting. It was found in [90] that the mean desktop illuminance level was over 400 lux in offices with no internal lighting. Considering that increases in the indoor illuminance level beyond 400 lux improve the perceived quality of lighting only slightly, the use of indoor lighting could likely be decreased when external illuminance levels are high [88],[90]. Therefore, there may be considerable potential to decrease the use of indoor lighting without affecting the perceived quality of lighting. However, it is important to note that the studies referenced here considered lighting a binary variable, (that is, lighting is either on or off) and that lighting usage may be different when lights can be dimmed.

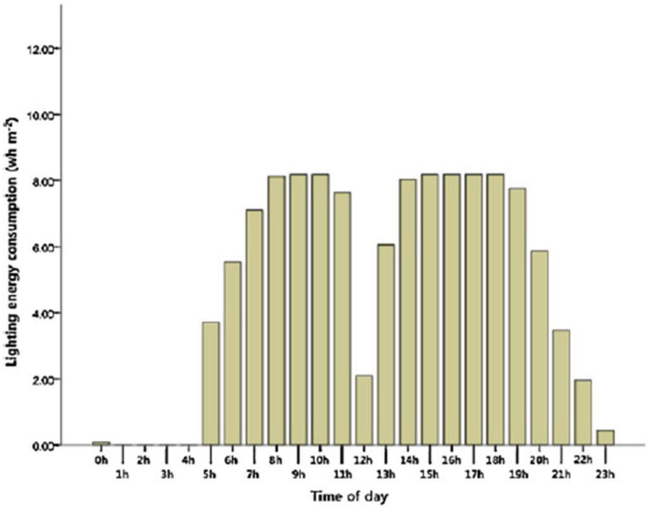


Figure 17: Daily lighting electricity consumption of an office building [89].

3.3 Cold appliances

Cold appliances are artificially cooled storage units that are usually used for the preservation of food products. In some cases, cold appliances can be used for storage of products other than food, such as medical supplies in hospitals [43]. Cold appliances used in residential buildings include refrigerators, fridge-freezers and standalone freezers, such as upright freezers and chest freezers [36]. Most commonly, household cold appliances consist of either a fridge-freezer or a combination of a refrigerator and a standalone freezer [36]. In wholesale and retail trade buildings, cold appliances may include cold rooms and display cabinets for both chilled and frozen foods [59]. Only the electricity consumption of cold appliance is considered in this thesis, as the share of other fuels can be assumed to be negligible.

3.3.1 Electricity consumption

The energy consumption of cold appliances in residential buildings, hospitals and wholesale and retail trade buildings is shown in Table 11. In hospitals, refrigerators and freezers are used for storing medical supplies and samples [43]. At around 2 – 4%, the share of cold appliances of the electricity consumption in hospitals is negligible. In hotels, cold appliances account for around 11% of total electricity consumption, though this value is based on the results of a single measurement study.

In residential buildings, the electricity consumed by cold appliances is mostly affected by number and type of cold appliances [36]. The average annual electricity consumptions of refrigerators, fridge-freezers and standalone freezers are 162 kWh, 427 kWh and 344.5 kWh, respectively. The average number of cold appliances in UK households is around 1.7. [36] At a share of 12% to 20%, cold appliances account for a significant share of household electricity consumption.

Table 11: Electricity consumption of cold appliances by building type.

Building type	**Reference**	**Share (%)**
Residential	[36],[91]	12 - 20
Hospital	[43],[92]	2 – 4
Hotel	[74]	11
Wholesale and retail trade	[58],[59]	25 - 60

Wholesale and retail trade buildings, convenience stores and markets in particular, are the largest consumers of refrigeration energy on a EUI basis. At 25% to 60% of the total electricity consumption, cold appliances represent a significant electrical load in these buildings. Larger stores, such as hypermarkets (markets with sales floor area of over 5000 m^2) represent the lower end of the range [58]. This is because larger stores tend to have relatively less floor space dedicated to food. Smaller food outlets like convenience stores can have a significant portion of their sales area dedicated to chilled and frozen food products. In these smaller stores, the share of cold appliances of the total electricity consumption can be as high as 60%. [58] Considering the high energy use intensity of these buildings (Table 6), it can be concluded that, in terms of EUI, wholesale and trade buildings are the most significant consumers of refrigeration energy.

3.3.2 Time of use

A refrigerator is cooled by pumping heat out of the insulated container using a compressor. This compressor is controlled by a thermostat that maintains the temperature between a lower and an upper limit. When the lower temperature limit is reached, the compressor is switched off, and the temperature in the refrigerator begins to increase. The compressor is switched back on when the upper temperature limit is reached. This repetitive behavior of cooling and heating is called the thermostatic cycle. [93]

Thermostatic cycle of a domestic refrigerator is shown in Figure 18 [94]. As can be seen, the duration of the thermostatic cycle is around one hour. However, the average internal temperature of the refrigerator increases after 12 PM, likely due to more frequent fridge door openings. To ensure that the temperature stays within the given limits, the length of the thermostatic cycle decreases. The durations of the cooling and heating portions of the thermostatic cycle depend on the properties of the compressor, ambient temperature and the thermal inertia of the refrigerator and its contents [93]. Thermal inertia is a property that determines a systems resistance to change in temperature. The cooling and heating cycles tend to be longer in refrigerators with higher thermal inertia [95]. Thermal inertia enables refrigeration systems to be used for demand response: the larger the thermal inertia, the longer the refrigerator can maintain its internal temperature without power [93]. Thermal inertia in refrigeration systems will be discussed further in Chapter 4.

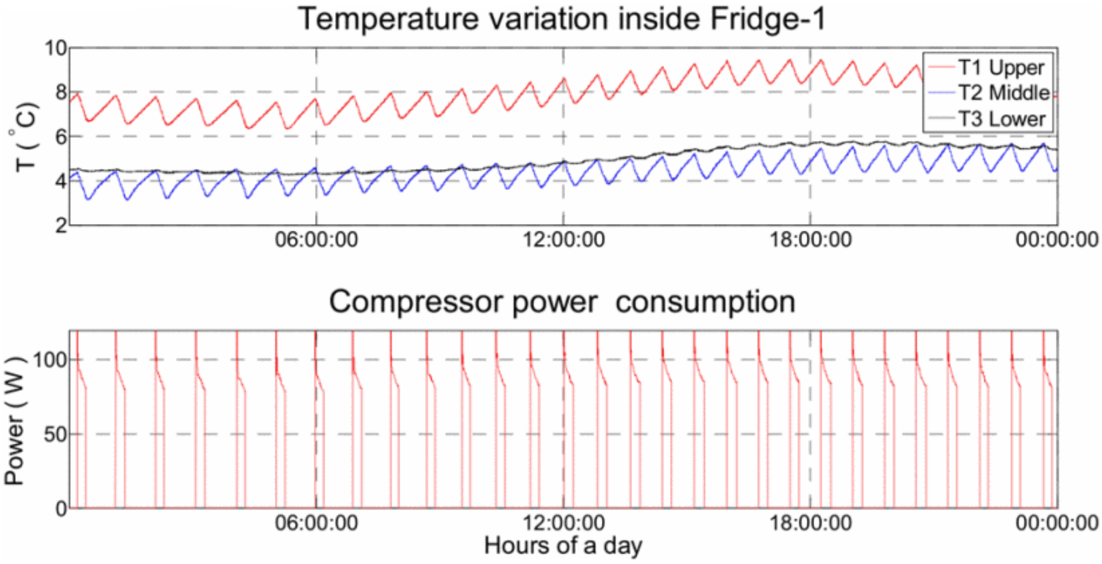


Figure 18: Thermostatic cycle of a domestic refrigerator [94].

3.4 Other appliances

This section focuses on electrical appliances other than AC, lighting and cold appliances. These other electrical appliances are divided into active appliances, and continuous and standby appliances. Active appliances are discussed in Subsection 3.4.1, and continuous and standby appliances are discussed in Subsection 3.4.2.

The daily average electrical appliance energy consumption profile of 250 UK residential buildings is shown in Figure 19 [96]. It can be seen, that appliance consumption is influenced by both building occupancy and the usual human diurnal rhythm. Households are usually occupied during the night, though consumption remains low until occupants wake up. While occupancy tends to lower during working hours, appliance consumption is almost twice as high compared to night. As expected, consumption is highest when occupancy is high and the occupant are awake: between 4 PM and 10 PM. It should be noted that Figure 19 does not display the true variability in appliance usage. The variability of electricity consumption of certain appliances is reduced due to averaging across households and times of year [96]. For example, the consumption of audiovisual and cooking appliances varies more significantly throughout the day than the graph would suggest [96]. The electrical appliances used in service buildings are like those used in residential buildings. Because of this, the electricity consumption patterns are similar but the consumption is timed differently due to dissimilar hours of occupancy. [49],[97]

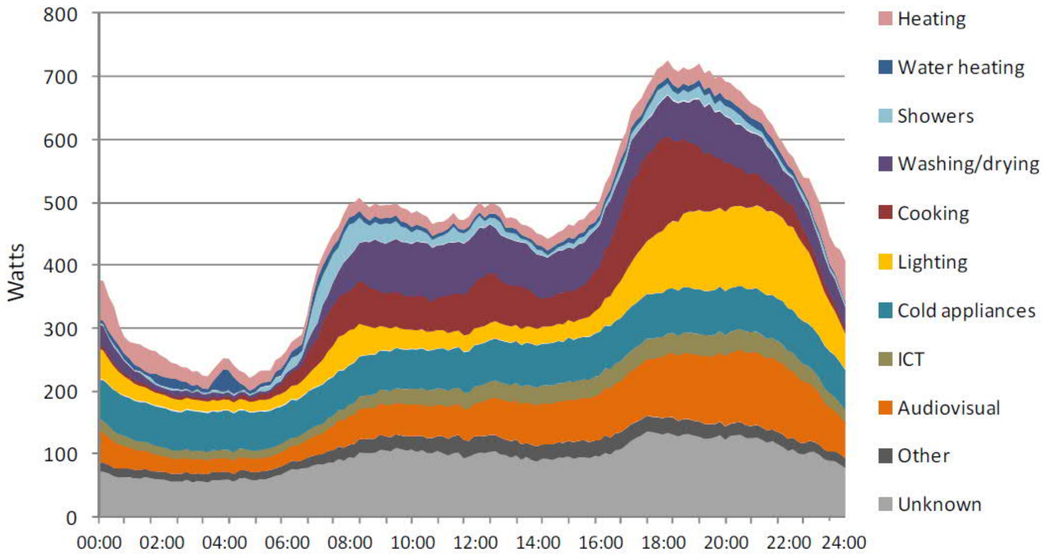


Figure 19: Average daily consumption profile of appliances in residential buildings [96].

3.4.1 Active appliances

Active appliances are electrical appliances that are actively switched on or off by the user. Active appliances are clearly either in use or not in use, they have no standby mode and consume no electricity when switched off. [49],[91] Common active appliances are cooking appliances and laundry, dishwashing and cleaning (LDC) appliances. The average annual consumption of some common active appliances in residential buildings is shown in Table 12 [36].

Table 13 shows the electricity consumption of cooking appliances in different building types. Cooking appliances include for example ovens, stoves and kettles [36]. The electricity consumption share of cooking appliances in residential buildings is around 14%. Cooking can be a significant contributor to consumption in service buildings with large scale catering services. In hotels, cooking appliances can consume 3 – 9% of total electricity. In hospitals, cooking appliances account for between 3% and 8% of total electricity consumption. For offices and educational buildings, the consumption share of cooking appliances is less than 2%. However, these numbers does not necessarily accurately reflect the total energy consumption of cooking appliances in service buildings. Electricity accounted for only around 15% of the total energy used for cooking in the hospitals monitored in [41]. This finding was supported by [74]: cooking appliances were shown to use significant amounts of natural gas in most types of service buildings. Therefore, cooking appliances may represent a more significant electrical load in buildings where mainly electricity is used for cooking.

Table 12: Annual electricity consumption of common active appliances.

Appliance	Consumption (kWh)
Washing machine	166
Washer dryer	243
Clothes dryer	394
Dishwasher	294
Cooker	317
Oven	290
Cooktop	226
Microwave	56
Kettle	167

On average, cooking appliances tend to be used for a short time, around 15 minutes to an hour [98],[99]. The power drawn by cooking appliances is usually in the range of 500 – 1000 W. The short usage duration combined with a relatively high drawn power means that the use of cooking appliances causes large spikes in the building consumption profile [91]. From Figure 19, it can be seen that in residential buildings, the cooking appliance consumption tends to be highest from 5 PM to 8 PM with smaller peaks throughout the day. Therefore, residential cooking appliances can contribute considerably to peak electricity demand.

Table 13: Electricity consumption of cooking appliances by building type.

Building type	Reference	Share (%)
Residential	[36]	14
Hospital	[74],[92]	2 - 8
Office	[74],[92]	< 1 - 2
Hotel	[74],[92]	3 - 9
Educational	[74],[92]	1 - 2

LDC appliances include for example washing machines, clothes dryers and dishwashers [36]. In residential buildings, the share of LDC appliances of the total electricity consumption is around 14% [36]. In most service buildings, these appliances do not account for a significant portion of the total consumption and their consumption is usually not reported [92]. In addition to electricity, LDC appliances often consume hot water [92]. The use of domestic hot water will be discussed in Chapter 5. LDC appliances draw less average power compared to cooking appliances but have a longer average usage duration [100]. For example, a washing machine may draw an average of 250 watts of power for a duration of 2 hours. However, occasional large power spikes happen during the washing program. The duration of these spikes is in the order of minutes and the power drawn can be as high as ten times the average. [100] Because of this, LDC appliances can have a noticeable impact on peak electricity demand. Compared to cooking appliances, the timing of consumption of LDC appliances tends to be more evenly distributed, with the largest consumption happening earlier in the day (Figure 19).

3.4.2 Continuous and standby appliances

Average annual consumptions of common continuous and standby appliances are shown in Table 14 [36]. Continuous appliances are appliances that are continuously switched on and require a constant connection to a power source. Continuous appliances include for example clocks, burglar alarms and broadband modems. Electricity consumed by continuous appliances can be seen as base consumption, as these appliances have a constant, continuous energy consumption profile. [49],[91] The instantaneous power consumed by these appliances is usually low. For example, a house alarm consumes around 67 kWh annually (Table 14), which equates to a constant power of about 7.6 W, assuming that the alarm is always on [36].

Standby appliances are active appliances that may have a non-zero energy consumption when not in active use [55]. Common standby appliances include for example information and communication technology (ICT) appliances and audiovisual appliances [36]. Standby appliances have three modes of operation: on, off and standby. Often the only way to ensure that standby appliances are truly off is to disconnect them from power supply, as for example televisions and gaming consoles tend to default to standby mode when “turned off”. [49],[91]

Table 14: Annual electricity consumptions of common continuous and standby appliances.

Appliance	Consumption (kWh)
Desktop computer	166
Fax/printer	160
Printer	21
Modem	62
Monitor	42
LCD TV	199
Radio	36
Gaming console	48
Speakers	31
Clock radio	20
House alarm	67

ICT appliances include for example personal computers and common computer products such as monitors, printers and modems. Table 15 shows the electricity consumption of ICT appliances in different building types [92]. In residential households without electrical heating, ICT appliances consume around 6% of total electricity, on average. ICT appliances tend consume a larger portion of total electricity in service buildings compared to residential buildings. They account for a significant portion of the total electricity consumption in offices and educational buildings: 19% and 22%, respectively. Electricity consumption of ICT appliances in hospitals and hotels is relatively similar to residential buildings.

On average, ICT appliances are on 19% and off 42% of the time. For the remaining 39%, these appliances are in the standby mode. Household ICT appliances tend to consume about 22% of their total electricity when in standby mode. [36] Similarly to continuous appliances, standby appliances have a constant and continuous electricity consumption when in standby mode. Standby consumption can be observed in Figure 19: from 12 AM to 8 AM ICT appliances are seldom in active use, meaning that the electricity consumption during this period can be mostly attributed to standby operation [36]. During the day, the consumption is higher, though it remains relatively constant with no clear consumption peaks. Therefore, household ICT appliances are not significant contributors to peak electricity demand.

Table 15: Electricity consumption of ICT appliances by building type.

Building type	Reference	Share (%)
Residential	[36]	6
Hospital	[92]	9
Office	[92]	19
Hotel	[92]	8
Educational	[92]	22

Audiovisual appliances are another common type of standby appliance. Audiovisual appliances include for example televisions, radios, speakers and gaming consoles. Like LDC appliances, these appliances do not contribute significantly to electricity consumption most in service buildings [92]. Audiovisual appliances consume around 14% of the total electricity consumption in residential households without electric heating. These appliances are on 36% of the time and off 16% of the time. They are in standby mode 48% of the time, during which they consume 16% of their total electricity demand. Similarly to ICT appliances, audiovisual appliances are usually not in active use during the night. [36] However, compared to ICT appliances, the consumption profile of audiovisual appliances is less uniform (Figure 19). After 7 AM, the consumption starts to steadily increase. A pronounced peak in consumption can be observed during the evening.

4 District heating and thermal inertia

The purpose of this chapter is to give preliminary information about some of the factors affecting the energy consumption and controllability of building thermal loads. Section 4.1 discusses district heating and how its characteristics relate to DR. Then, in section 4.2, the concept of thermal inertia is presented and its implications to DR of thermal loads are discussed.

4.1 The district heating system

The district heating (DH) system is an underground network of pipes that connects buildings in a certain area so that heat can be supplied to them from a centralized heating plant or multiple distributed heating plants. Thermal energy is supplied by heating water in the heating plants and transporting it via the district heating network. [101] The thermal energy is supplied to buildings from substations. Substations are the connection between the distribution network (the primary network) and the internal space heating and hot water systems of the building (the secondary network). [102] Usually, the substations are connected indirectly, meaning the primary network water does not circulate in the buildings [102]-[104]. In Finland, the temperature of the distribution water is usually between 65 °C and 115 °C, depending on the outside temperature [103],[104]. The temperature of the return water is usually around between 40 °C and 60 °C. However, in recent times, there is a trend towards lower distribution and return water temperatures [105]-[107]. Figure 20 shows a simplified connection scheme between the DH network and a building [102].

In 2017, district heating systems supplied around 10% of the global total heating demand. In parts of Europe, China and Russia, DH is utilized considerably more widely compared to the global average. [108] In Finland, district heating accounted for 46% of the total heating generation in 2012 [109]. Over 90% of residents in large Finnish cities live in buildings connected to district heating networks. Furthermore, around 95% of Finland's newly built residential apartment buildings, office buildings and wholesale and retail trade buildings are connected to DH. [110] It is generally believed that district heating is going to play a significant role in the sustainable energy systems of the future [108]-[114].

District heating is primarily based on combined heat and power generation (CHP) supported by heat only boilers [115]. CHP refers to the use of a power plant to simultaneously generate useful heat and electricity. In Finland and Denmark, where district heating is extensively used, CHP accounts for around 64% and 70% of district heating production, respectively [116],[117]. As the share of variable renewable energy sources in electricity generation increases, it becomes increasingly important to operate DH CHP plants to meet the requirements of the power system. This entails running DH CHP plants to meet the electricity demand rather than the heating demand. [118],[119] However, CHP plants often produce electricity and heat at a fixed ratio [115]. This is because the highest possible efficiency is achieved when the CHP plant is run at full power under the designed optimal heat-to-power ratio [119]. DR of thermal loads can be used to smooth out differences in heating generation and demand, since DR measures can be used to influence the end-use customer heating loads, either by underheating or overheating the building [120],[121].

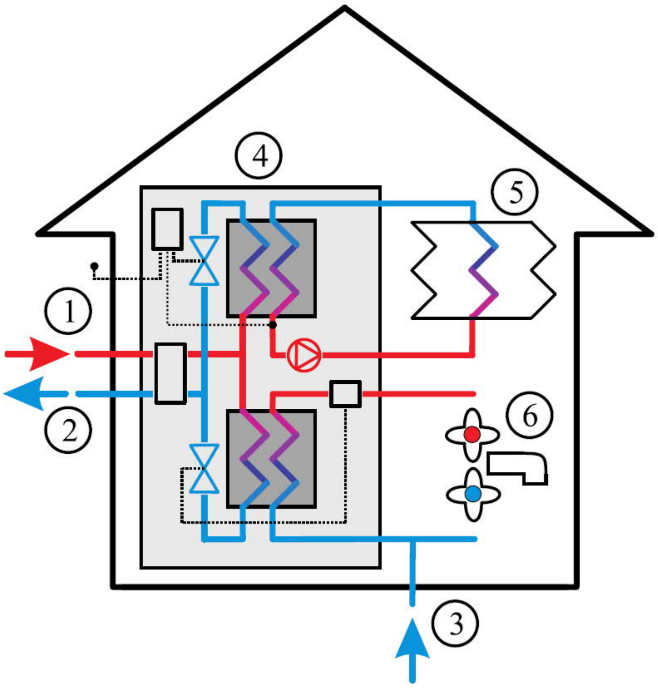


Figure 20: Substation connection scheme. (1) Distribution water. (2) Return water. (3) Incoming cold tap water. (4) DH substation. (5) Radiator system. (6) Water tap. [102]

In DH networks, the customer heat demand can be fulfilled by controlling two factors: water mass flow and temperature difference. This means that there are two ways to influence the amount of heating energy the customers receive. The first one is to either increase or decrease the water mass flow, depending on whether the building is to be overheated or underheated. The change in heat supply propagates in the DH network at the speed of sound in water (around 1000 meters per second). The second one is to change the temperature difference between the supply and return pipes. In this case, the change in heat supply propagates at the flow rate of the water, which much slower (between 1 and 3 meters per second). As a result, changes due to alteration the of flow rate can be notices in a few seconds, whereas changes due to alteration of temperature difference can take from minutes up to hours to take effect, depending on the customer’s proximity to the plant. [122]

When the heat supplied to a district heating network is changed, the customers are affected differently. If the heat supplied to the network is less than the demand, the customers closest to the heating plant can still receive sufficient heating, whereas the customers at the peripheries of the network may not receive any heating. This discrepancy is caused by differences in the differential pressure between supply and return pipes, which is controlled by distribution pumps. As there usually are no pumps at the buildings of the customers, the customers closest to the heating plant get the largest differential pressure and therefore more heating. [122] Figure 21 shows a map of the DH network of the Greater Copenhagen area [123]. There are significant differences in the distances between heating plants and the closest customers and the farthest customers.

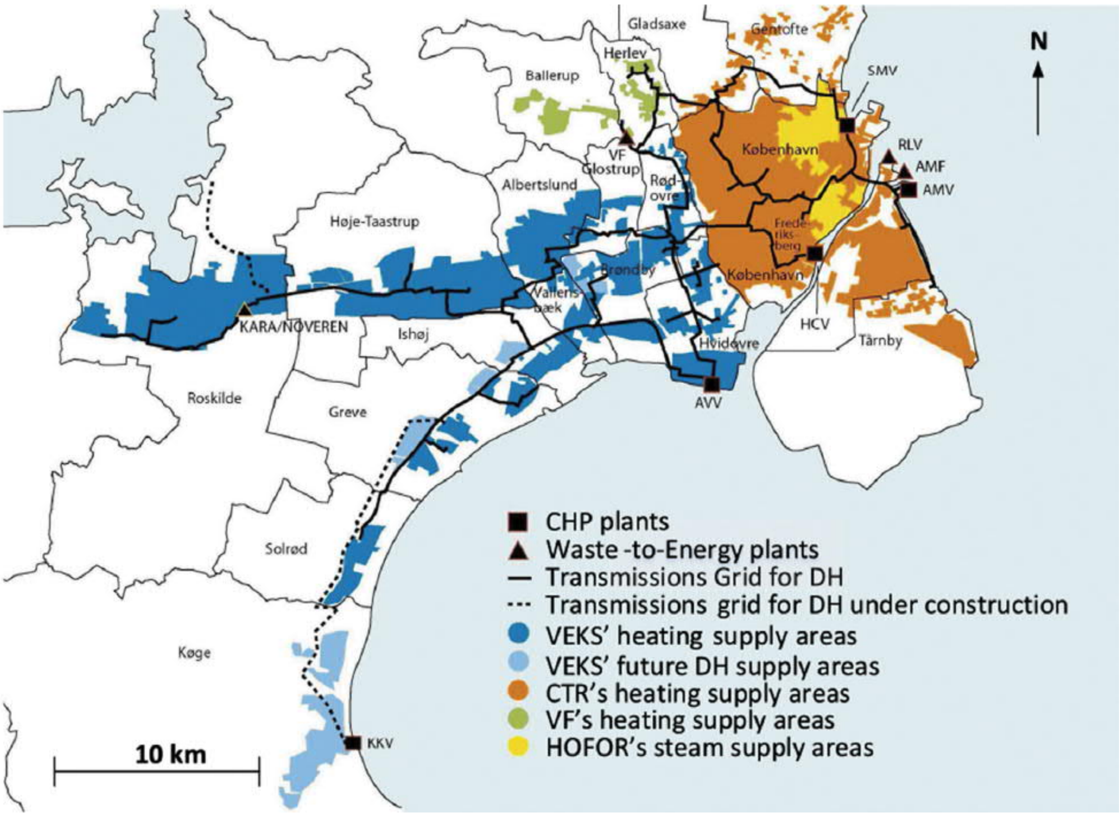


Figure 21: The DH network of the Greater Copenhagen area [123].

4.2 Thermal inertia

4.2.1 Terminology

Thermal characteristics of buildings are described in the literature with many different terms. Some of these terms are used interchangeably, and the meaning of the terms may differ between sources. In the DSM literature, the two properties most commonly discussed are: thermal capacity and thermal inertia.

Thermal capacity is synonymous with heat capacity. It is defined as the property that determines the amount of heat required to produce a unit temperature change in a given system. Thermal capacity is an extensive property, it is dependent on the size of the system. The SI unit of thermal capacity is joule per kelvin (J/K). [124] A system's thermal capacity can be calculated according to Equation 1. The term "thermal mass" is often used when referring to the buildings' thermal capacity [125]-[127].

$$C = \frac{\Delta Q}{\Delta T} \tag{1}$$

Where C is the thermal capacity, ΔQ is the heat change of the system and ΔT is the resulting temperature change.

Thermal inertia is a property that determines a system's resistance to change in temperature. Thermal inertia is related to the material's volumetric heat capacity and thermal conductivity. Unlike thermal capacity, thermal inertia is an intensive property, meaning that it is independent on the size of the system. Thermal inertia can be calculated according to Equation 2 and its SI unit is $J/m^2\,K\,s^{1/2}$ [128].

$$I = \sqrt{k \rho c_p} \tag{2}$$

Where I is the thermal inertia, k is the thermal conductivity, ρ is the density and c_p is the specific heat capacity.

4.2.2 Thermal inertia in buildings

The thermal inertia of a building enables it to act as a short-term thermal energy storage [129]. The different structures of the building acting as thermal energy storages help dampen variations in the building indoor temperature. This means that the building thermal loads can be periodically overheated or underheated without large effects on the indoor temperature. By using this type of load control strategy, building thermal loads can be utilized as a part of DR. [130] The acceptable duration of load control periods is determined by the building's thermal inertia. Buildings with large thermal inertias are better suited for DR of their thermal loads. The larger the thermal inertia, the more resilient the building is against indoor temperature changes due to altered heat supply. Therefore, high thermal inertia means that the occupants are less likely to experience a decline in thermal comfort during a DR period.

A building's thermal capacity is determined by the thermal capacities of the solid materials and the indoor air [129]. Solid materials include the building structure components, such as walls, ceiling and floors. The building structure components are often made of materials with high thermal capacities, such as concrete and bricks. [131] The solid materials are heated by the space heating system (radiators or floor heating), mostly through radiation [129],[132]. In addition, the space heating systems themselves consist of materials that can have significant thermal capacity, such as metal piping and water. Therefore, the thermal inertia of a hydronic space heating system is likely larger compared to a direct electric heating system, as these do not have circulating water.

The thermal inertia of buildings with a floor heating system is considerably higher than buildings heated by a radiator system [133],[134]. This is due to the difference in heat transfer methods and the comparatively larger thermal capacity of the floor heating system [134]. The difference is further affected by the type of floor heating and the thermal capacity of the flooring materials. Flooring materials with a high thermal capacity, such as concrete, are often used with the in-slab floor heating system, which is the most common type of floor heating. [133],[135] Figure 22 shows the required time to increase the indoor temperature by 10 °C for different heat transfer systems [134]. The required time for an in-slab floor heating (ISFH) is the largest, closely followed by light floor heating (LFH). For both types of floor heating systems, the time it takes for the indoor temperature to increase by 10 °C is around 6 hours, whereas for the radiator system it is just under 3 hours.

Compared to the solid materials of the building, the indoor air has a considerably smaller thermal capacity [130]. Indoor air is heated partially by the space heating system and the building envelope as well as by the heating system of the ventilation intake air [130],[132]. As can be seen from Figure 22, a building that is heated solely by an air-heating system has a lower thermal inertia than buildings using radiator or floor heating systems.

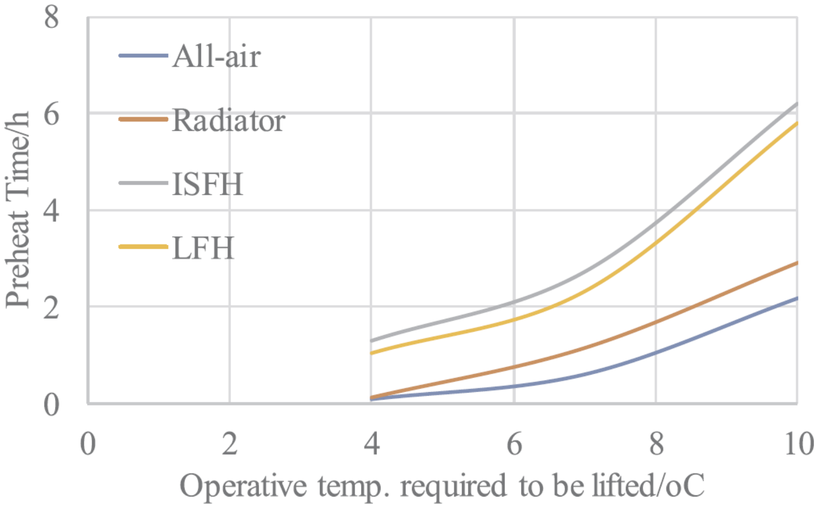


Figure 22: Indoor temperature response to overheating [134].

During a DR period, a high rate of ventilation tends to decrease the thermal inertia of a building [132]. This is because when the temperature of the indoor air changes relative to the temperature of the solid materials, heat transfer will occur between the indoor air and the solid materials [130]. The faster the indoor air is replaced by outdoor air, the faster the temperatures of the solid materials of the building change. Therefore, buildings with lower ventilation rates maintain their internal thermal environment longer during DR periods, and therefore preserve thermal comfort of the occupants more effectively.

The effect of ventilation on the building thermal inertia can be observed from Figure 23. The figure shows the indoor temperature change of a government center building during a period of no heat supply. When ventilation is left on, the indoor temperature decreases by 2 °C (from 21 °C to 19 °C) in 4 hours. It takes around the same amount of time for the temperature to increase by 2 °C after the heat supply is resumed. When of ventilation is turned off, the time it takes for the indoor temperature to decrease by 2 °C is 5:50 hours. [132] The effect of ventilation is significant: the duration corresponding to an indoor temperature decrease of 2 °C is almost 50% greater when the ventilation is shut off. Furthermore, when the heat supply is resumed, the indoor temperature increases faster. It takes roughly 3 hours for the temperature to increase by 2 °C. Therefore, building thermal inertia could likely be increased by reducing the ventilation rate.

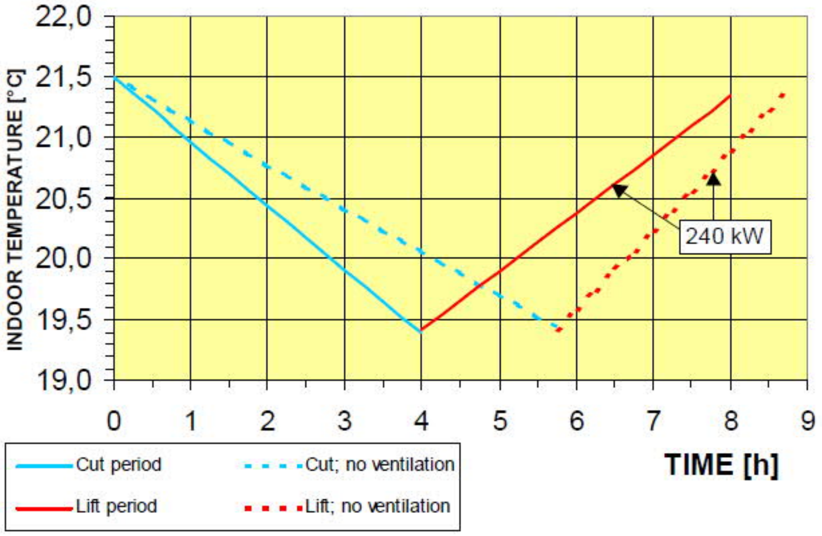


Figure 23: Indoor temperature response to an interruption in heat supply, with ventilation on and off [132].

Figure 24 shows the indoor temperature change of two buildings during a period of no heating. Building A is passive house with a thermal capacity of 200 Wh/(K m^2) and building B is a lightweight building with a thermal capacity of 40 Wh/(K m^2). The outdoor temperature is -20 °C. [136] As can be seen, there is a nonlinear relationship between the building thermal capacity and the rate of indoor temperature change. Building A has five times greater thermal capacity than building B, the time elapsed until an indoor temperature of -5 °C is reached is ten times greater for building A. This is because thermal inertia is dependent on more than the building's thermal capacity. As a passive house, building A is well insulated and equipped with an efficient exhaust air heat recovery system [136]. These factors decrease the air leakage and therefore increase thermal inertia independently of thermal capacity.

It is also noteworthy that the rate of indoor temperature change is dependent on the temperature difference between the indoor and outdoor air. The indoor temperature change slows down as the temperature difference between the inside and outside air decreases. Because of this, it is likely that the flexibility of thermal loads of buildings with small thermal inertias decreases significantly as the outdoor temperature decreases. On the other hand, buildings with exceptionally high thermal inertias may have lower flexibilities when the outdoor temperature is not sufficiently low. In the case of building A, it was estimated that heating was required only when the outdoor temperature was continuously under between -5 and -10 °C [136].

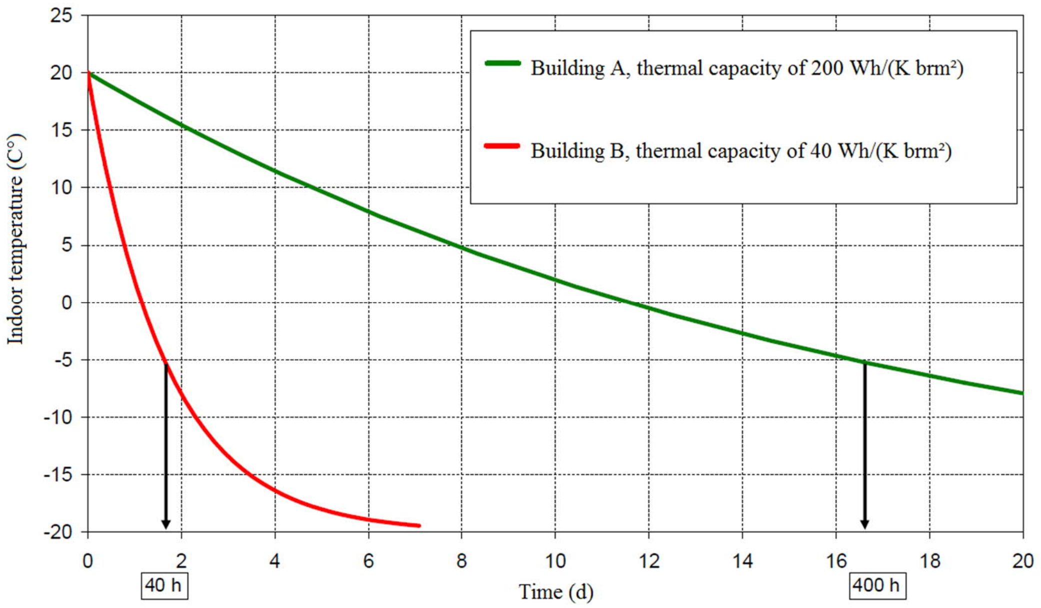


Figure 24: Indoor temperature change during a period of no heating. Edited from [136].

4.2.3 Thermal inertia in refrigeration systems

Thermal inertia enables refrigeration systems to maintain their thermal environment in an acceptable range for some time without power, similarly to buildings. This could allow refrigeration systems to be used for DR. In buildings, the limitations of the thermal environment are determined by the thermal comfort requirements of the occupants. In refrigeration systems, the preservation of the food products is the limiting factor [137]. The acceptable temperature limits for different food products are usually set by the law [138].

A refrigeration system's thermal inertia is determined by the contents of the cooling unit, the level of insulation and the indoor temperature [139]. Furthermore, thermal inertia can be increased by reducing the cooling power only partially and by using pre-cooling strategies, where the system is cooled to a lower temperature before the power is cut [140].

Open refrigeration units, such as display cabinets and chiller cabinets tend have a smaller thermal inertias compared glass-doored freezers and chest freezers. This is likely due to lack of insulation: over 75% of the heat losses in open front chilled food display cabinets are due to infiltration [58]. Figure 25 shows the thermal response of an open display cabinet during maximum cooling followed by a period of no cooling [140]. During the cooling period, the temperature of the display cabinet decreased at a rate of around 0.84 °C per minute. During the period of no cooling, the temperature increased at a rate of around 0.24 °C per minute. [140] The low thermal inertia of the open display cabinet is evident from the fast temperature responses: in just around 5 minutes, the temperature of the cabinet had increased back to level it was at before the pre-cooling. Therefore, the flexibility of such non-insulated cold appliances is likely limited to short-term load reductions. For better insulated domestic and commercial refrigeration systems, using a pre-cooling strategy, the acceptable duration of no cooling is estimated to be between 30 minutes and 1 hour [141].

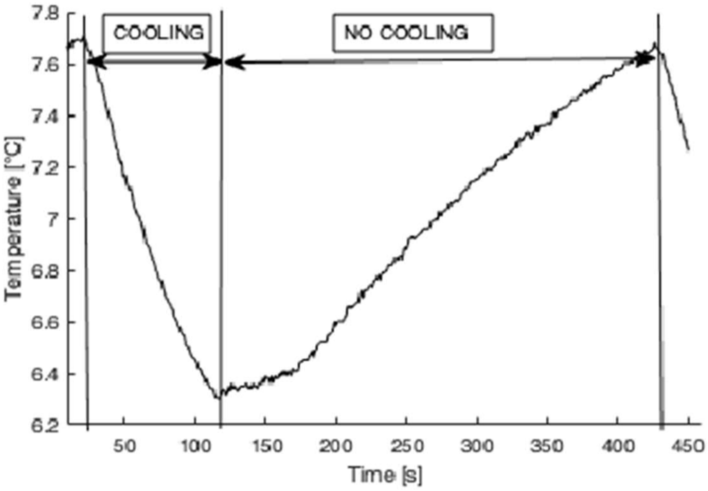


Figure 25: Thermal response of a refrigerated display cabinet [140].

5 Thermal loads

This chapter discusses building loads that consume heating energy. In this thesis, thermal loads are defined as the different systems that provide heating to the customer. Usually, the heating consumption of a building is divided into three distinct systems that supply the heating demand of customers: space heating, heating of ventilation air and domestic hot water (DHW) [142]-[145]. The purpose of this chapter is to describe the building thermal loads and discuss the characteristics most relevant to demand response. Section 5.1 focuses on describing space heating system types and the differences between them. Heating of ventilation air and domestic hot water are discussed in sections 5.2 and 5.3, respectively. Finally, in Section 5.4, the times of use of the different building thermal loads are examined.

5.1 Space heating

Space heating systems are used to transfer heat to the building living spaces in order to maintain comfortable indoor temperatures. The term “space heating system” usually refers to the primary heating system of a building. The space heating system is usually the largest thermal load in a building. Space heating usually accounts for around 45 – 60% of a building’s total heating consumption 45 – 60%, though this depends on factors such as DHW usage and heating consumption of ventilation air [132],[146],[147].

Only hydronic space heating systems are considered in Subections 5.1.1, 5.1.2 and 5.1.3. Moreover, these subsections focus on the most common types of hydronic space heating systems, which are radiators and hydronic floor heating [135]. The differences between electric heating and hydronic heating systems will be discussed in Subsection 5.1.4.

5.1.1 Radiator system

A hot-water radiator is a type of central heat transfer system. The hot water is circulated in the radiator by using a water circulation pump. Wall-mounted radiators are usually placed underneath windows to reduce heat loss due to downdraughts. Different types of radiator systems include sectional cast-iron columns, large-tube units and panel radiators, with panel radiators being the most common. [135] Radiators are by far the most common form of heat transfer system in Finnish apartment buildings and service buildings [148],[149].

Radiators heat the indoor air mostly by convection and the solid materials by radiation [129],[150]. The heating is controlled by altering either the temperature of the circulating water or the flow rate of the water [150],[151]. The control is achieved with thermostats that are usually user controlled, though remote-controlled thermostats are available [151],[152].

5.1.2 Floor heating

A floor heating system is a type of radiant panel heating system that supplies heat directly to the floor, wall or ceiling. The most common type of hydronic floor heating is slab on grade, where the floor heating tubing is embedded in a screed [135]. In Finland, floor heating is mostly used in detached houses. However, in recent years, hydronic floor heating combined with district heating has become more common in new apartment buildings and service buildings, especially in bathrooms [149].

Unlike in radiator systems, the tubing of a floor heating system does not directly heat the indoor air by radiation and convection due to the way the tubing is installed. Instead, the conductive heating tubing or the circulating hot water tubing heats the building structures by conduction [153]. The structures, namely the floor, then heats the indoor air mainly via radiation [153]. The method of heat transfer to the indoor air is an important factor to consider, as it affects the building's thermal inertia.

5.1.3 Differences between radiator and floor heating systems

The differences in thermal inertia between buildings heated by radiator systems and floor heating systems were discussed in Chapter 4. In addition, the type of space heating system affects the magnitude of building heating consumption. Multiple studies have compared the heating consumption of buildings with radiator systems and buildings with hydronic floor heating. [154] showed that in well-insulated buildings, the heating consumption of a radiator heating system can be up to 10% greater compared to a floor heating system. [155] found a that when the radiator heating system was replaced with a hydronic floor heating system, the annual heating consumption decreased from 103921 kWh to 96204 kWh, resulting in annual savings of around 7.5%. [156] showed that, when combined with a solar-groundwater heat pump system, a floor heating system can save up to 19% energy, compared to a traditional radiator system. It is important to note that the findings of [154] and [155] were based on simulation models and numerical analysis and that occupant behavior was not accounted for. As mentioned in Chapter 2, occupant behavior can have a large impact on the heating consumption, particularly in newer buildings where floor heating systems tend to be more common.

Other studies have shown that the heating consumption of buildings with floor heating is actually higher. A simulation study showed that both the annual heating consumption (Figure 26) and the peak load (Figure 27) were higher when floor heating was used, compared to a radiator system [157]. The comparison was done for non-renovated, lightly removed and extensively renovated buildings. A measurement study comparing radiators and floor heating in Swedish households showed that the heating consumption of floor heated households was 15 – 25% higher than radiator heated buildings [158].

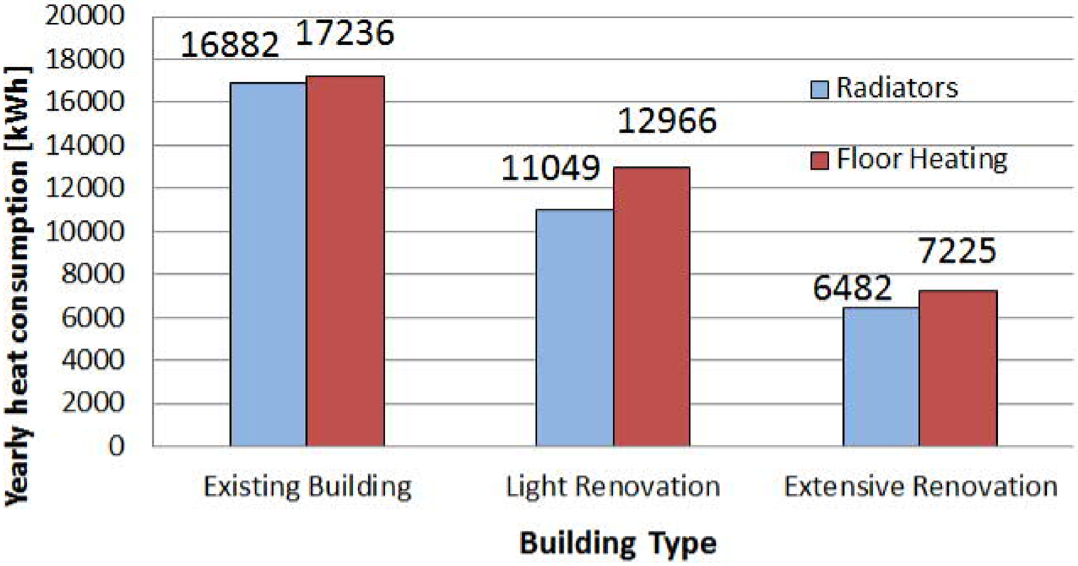


Figure 26: Comparison of floor heating and radiator heating: annual consumption [157].

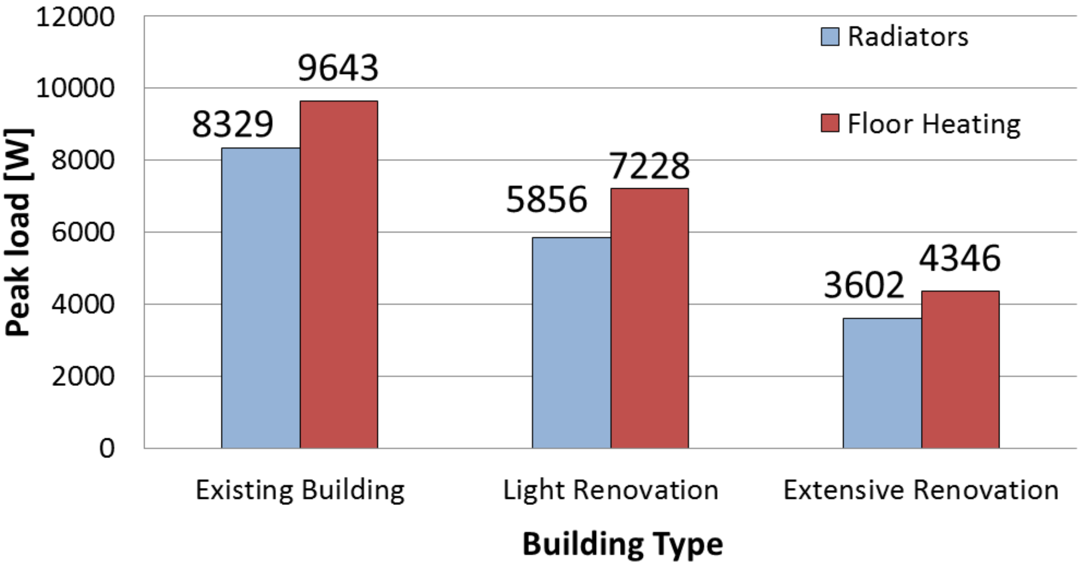


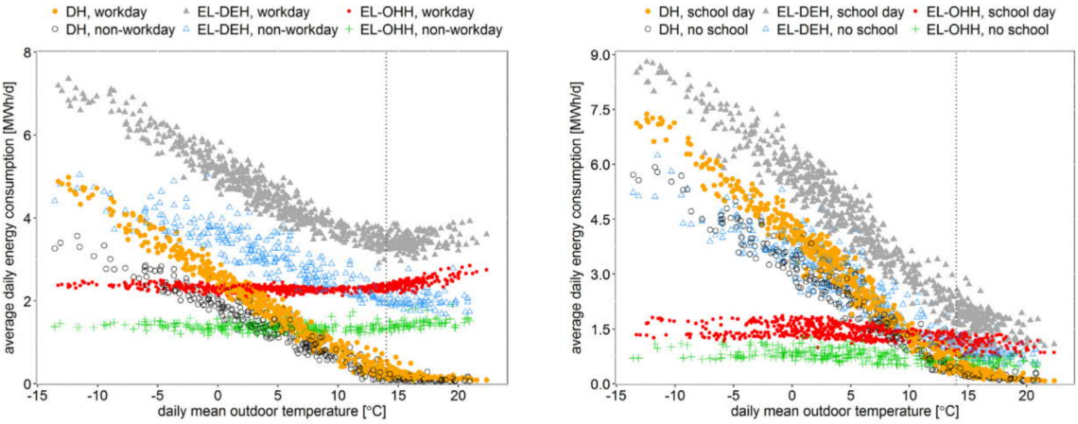
Figure 27: Comparison of floor heating and radiator heating: peak load [157].

5.1.4 Differences between district heating and electric heating

District heating is a centralized form of heating, whereas electric heating is a local form of heating. The two heating methods are suited for different types of buildings: district heating is used in residential apartment buildings and service buildings in cities, whereas electric heating is mostly utilized in detached houses. In Finland, electric heating is by far the most common heating method in detached houses. According to the building stock register, 44% of detached houses are heated using electric heating [159]. However, with the recent increase in popularity of geothermal heating, the market share of electric heating in detached houses has decreased from over 70% in 1995 to around 30% in 2017 [159]. The prevalence of DH in Finland was discussed in Section 4.1.

Residential buildings heated by DH tend to have a higher heating EUI, compared to residential buildings heated by electric heating. The Swedish energy authority reported that in 2018, the heating EUI of Swedish one- and two-dwelling buildings was 79 ± 5 kWh/m^2 and 120 ± 5 kWh/m^2 for direct electric heating (DEH) and DH, respectively. At 74 ± 5 kWh/m^2, the heating EUI of hydronic electric heating is like that of DEH. [160] Similar findings were reported for Serbian residential buildings: heating EUI of households using DH was found significantly higher compared to households using electric heating [161]. The higher heating EUI of buildings using DH may be explained by larger heat losses compared to electric heating systems [162].

Figure 28 shows the measured average daily electricity and DH consumption in Norwegian office and school buildings [162]. The metered buildings used either DH or DEH as the heating method. The heating consumption of both heating systems varies similarly as a function of outdoor temperature, as can be seen from Figure 28.



(a) Office buildings **(b)** Schools

Figure 28: Average daily DH and electricity consumption of office and school buildings as a function of daily mean outdoor temperature [162]

One key difference in the time of use between the two heating systems is that the heating consumption starts later in office buildings with DEH, compared to DH [162]. This is likely explained by the fact that the thermal inertia of a building using DEH is lower and therefore the heat is distributed faster. Moreover, school buildings using DH tend to use less temperature setback during nights and non-school days when compared to schools with DEH [162]. This means that the average indoor temperature of buildings using DH is higher during periods when the building is not occupied. This may be due to buildings using DEH having more advanced control systems and therefore being able to utilize temperature setback more easily [162]. Another potential explanation is buildings using DH having higher thermal inertias. Due to slower temperature responses, it would take longer for these buildings to reach their normal operating temperatures after a temperature setback.

5.2 Ventilation air

Building ventilation is the intentional provision of outdoor air into the indoor space. Providing a healthy indoor air quality with ventilation is necessary, as it has been extensively shown that indoor air quality is associated with occupant health, comfort and productivity [163]-[165]. In service buildings and residential apartment buildings, ventilation is provided by mostly mechanical ventilation [166]. In a mechanical ventilation system, outdoor air is replaced by using supply and exhaust fans. During the heating season, the supplied ventilation air must be heated. In residential apartment buildings with no exhaust air heat recovery, the heating of ventilation air can account for between 25 and 35% of the heating consumption [146]. Exhaust air heat recovery systems are common in Finland. This is because the Ministry of Environment has decreed that all ventilation systems must recover an amount of heating energy equal to 30% of the ventilation air heating consumption [167].

Since the supplied ventilation air must be heated, rate of ventilation can have a significant impact on a building's heating consumption. Multiple studies have shown a close to linear relationship between building ventilation rate and heating energy consumption [168]-[170]. Figure 29 shows the relationship between the ventilation rate and natural gas consumption in an office building [170]. Natural gas use is typically associated with heating consumption [169]. The magnitude of effect of ventilation rate is dependent on the weather conditions: the effect is significant in the winter, small in the spring and non-significant in the summer. Doubling the ventilation rate in the winter increases the natural gas EUI by around one third. Therefore, during a DR period, building heating consumption could be reduced by reducing the ventilation rate.

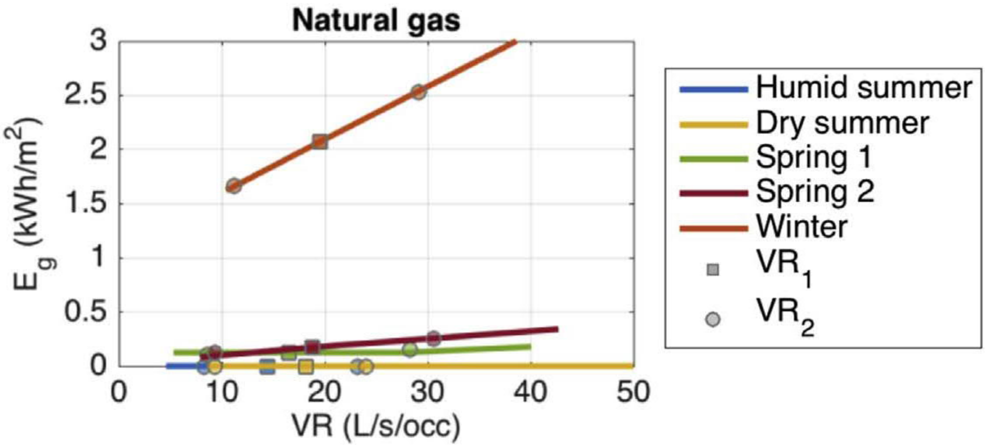


Figure 29: Ventilation rate's effect on the natural gas consumption in an office building [170].

The minimum ventilation rates required to maintain acceptable indoor air quality are usually set by the law. In Finland, the Ministry of the Environment set the minimum ventilation rate to 6 dm^3/s per person in most buildings in 2012 [171]. Since then, the ministry invited FINVAC (The Finnish Association of HVAC Societies) to revise these guidelines [172]. In order to determine if building ventilation rates could feasibly be reduced during a DR period, measured building ventilation rates are compared to the guidelines (Tables 16 – 18). Office buildings, school buildings and residential apartment buildings were chosen for the comparison, because the occupants tend to remain in these buildings for long durations at a time. Due to the nature of occupancy, the potential adverse effects of reducing ventilation rate would likely be most significant in these buildings. For office and school buildings, the revised guidelines are used for comparison. For residential apartment buildings, the regulation set by the Ministry of the Environment is used, as revised guideline is not available.

For office buildings (Table 16), the ventilation rates differ significantly between buildings, though the measured ventilation rates were higher than the guideline for all buildings. The discrepancies between the measurements and the guideline value were most significant in the American offices: the mean ventilation rate was almost ten times as high as the Finnish guideline. For school buildings (Table 17), the measured ventilation rates were much closer to the guideline. The mean ventilation rate of the 59 schools monitored in [173] was actually below the guideline value. For residential apartment buildings (Table 18), ventilation rates were in all cases above the guideline value, though by not as much as in office buildings. It can be concluded that the heating of ventilation air has a larger impact on the energy consumption of offices when compared to schools and residential apartment buildings. Based on these findings, ventilation rates could feasibly be reduced in office buildings but likely not in school or residential apartment buildings.

Table 16: Ventilation rates in office buildings.

Country	**Reference**	**Ventilation rate (dm^3/s per person)**
USA	[174]	55 ± 74
Finland	[175]	9.3 - 24
Finland	[176]	20
Sweden	[177]	22 ± 17
Switzerland	[178]	11 - 50
Guideline		6

Table 17: Ventilation rates in school buildings.

Country	**Reference**	**Ventilation rate (dm^3/s per person)**
USA	[179]	10.07 ± 6.91
Finland	[180]	13 ± 4
Finland	[173]	5.7 ± 3.8
Guideline		6

Table 18: Ventilation rates in residential apartment buildings.

Country	**Reference**	**Ventilation rate (1/h)**
Finland	[181]	0.81 ± 0.85
Finland	[182]	0.64 ± 0.3
Greece	[181]	1.3 ± 1.1
Switzerland	[181]	0.83 ± 0.46
Czech Republic	[181]	0.75 ± 0.43
Guideline		0.5

5.3 Domestic hot water

The third distinct building thermal load is DHW. Domestic water needs to be heated to both meet the operational requirements of certain appliances and to satisfy the thermal comfort requirements of the occupants [183]. In buildings connected to district heating networks, the thermal energy from the distribution water is transferred to the incoming cold tap water via a heat exchanger (Figure 20). In buildings with electric heating, DHW is usually heated using electric resistance heaters [184]. The main uses for DHW include washing, bathing, drinking, laundry and cleaning [185]. In residential buildings, DHW accounts for 15 – 20% of the total heating consumption [146],[147]. In service buildings, such as offices, DHW can consume less than 5% of the total heating energy [132]. The largest factors affecting the DHW consumption of a building are occupancy level, appliance ownership and occupant behavior [183].

Residential buildings are by far the largest consumer of DHW, accounting for almost 72% of the total DHW volume [186]. Moreover, residential buildings are also among the most energy intensive buildings in terms of DHW. Table 19 shows the heating EUI of different building types reported in the Finnish building code [187].

Table 19: DHW heating energy use intensity of different building types.

Building type	**Heating energy use intensity (kWh/m2 a)**
Residential	35
Office	6
Hotel	40
Educational	11
Hospital	30

DHW consumption is usually reported in liters per day per person (L/d/person). One liter of DHW corresponds to around 0.6 kWh of heating energy, assuming that water is heated from 5 °C to 55 °C [187]. In Finnish residential apartment buildings, the measured mean and median values of the annual DHW consumption are 42 L/d/person and 35 L/d/person, respectively [185]. Figure 30 shows the DHW consumption for different household sizes [185]. The number of occupants has a significant impact on the DHW consumption: the smaller the number of occupants, the larger the per occupant consumption. The mean DHW consumption in one person households is around three times of that in six-person households. Moreover, the variation between households is larger for smaller households.

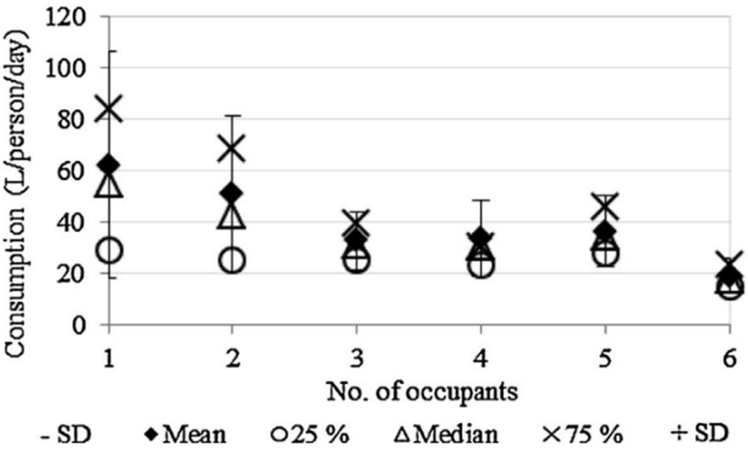


Figure 30: DHW consumption of different sized households [185].

5.4 Time of use

5.4.1 Space heating and heating of ventilation air

The heating consumption of the building space heating system varies close to linearly with the temperature difference between the indoor and outdoor air [188]. As previously shown in Section 5.2, the energy consumed by the heating of the ventilation air depends on both the outdoor temperature and the ventilation rate. If the ventilation rate is only adjusted to satisfy the indoor air quality requirements, the heating consumption of the ventilation air can be assumed to vary linearly with outdoor temperature as well.

Heating degree days (HDD) are often used when estimating building heating consumption. HDD is defined as the difference between the daily average outdoor temperature and a predefined base temperature. In Finland, the base temperature is set at 17 °C. The use of HDD assumes that if the average outdoor temperature is above a certain limit, the heating consumption of buildings is zero. [188] Therefore, the annual consumption of space heating and heating of ventilation air can be estimated using the number of monthly HDDs. Figure 31 shows the monthly number of HDDs for two Finnish cities [188]. The data is based on the monthly averages for the years 1981 – 2010. As can be seen, the number of monthly HDDs is a U-shaped curve where the number of HDDs is highest during the winter months, and lowest during the summer. Moreover, the number of HDDs depends strongly on the climate zone: the average number of yearly HDDs is around 60% greater in Ivalo (latitude of around 68° N) compared to Helsinki (latitude of around 60 ° N).

The daily heating consumption profiles of office buildings in different average outdoor temperatures can be observed in Figure 32 [189]. The buildings are divided into three groups based on their energy use. A distinct peak in heating consumption can be observed in the early morning. This happens largely because the space heating is often switched off for the night, leading to a peak in consumption when the heating is turned back on [190]. The heating consumption profiles shown in Figure 32 were measured during the weekdays [189]. Residential buildings have a similar consumption profile to those shown in Figure 32. Furthermore, the relationship between of the magnitude of consumption and the relative size of the morning peak in residential buildings is similar to that observed in office buildings. [191]

As can be seen from Figure 32, the size of the morning peak depends on both the magnitude of the heating consumption and the average outdoor temperature. As the building heating consumption decreases, the relative size of the morning peak increases. This phenomenon can be observed both between the groups with different consumption levels and within the groups as the outdoor temperature changes. Moreover, this rebounding behavior is present whenever thermal loads are switched back on after a period of lower use or no use. Therefore, DR of thermal loads leads to similar peaks in heating consumption [132],[192],[193]. The rebound effects resulting from DR are similar in buildings using DH and building using electric heating [132],[193]. It is reasonable to assume that rebound consumption peaks caused by DR measures are similarly affected by the outdoor temperature and heating consumption of the building, as peaks resulting from normal temperature operation of the building. After a consumption peak, the heating consumption initially decreases very quickly, after which it slowly reaches equilibrium.

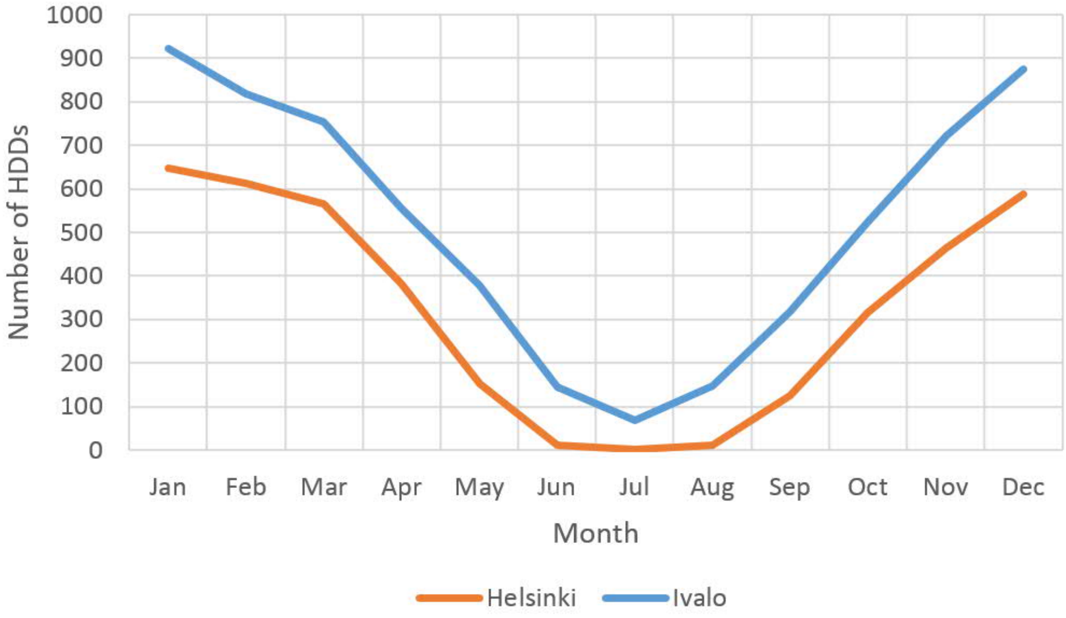


Figure 31: Average monthly HDDs in Helsinki and Ivalo.

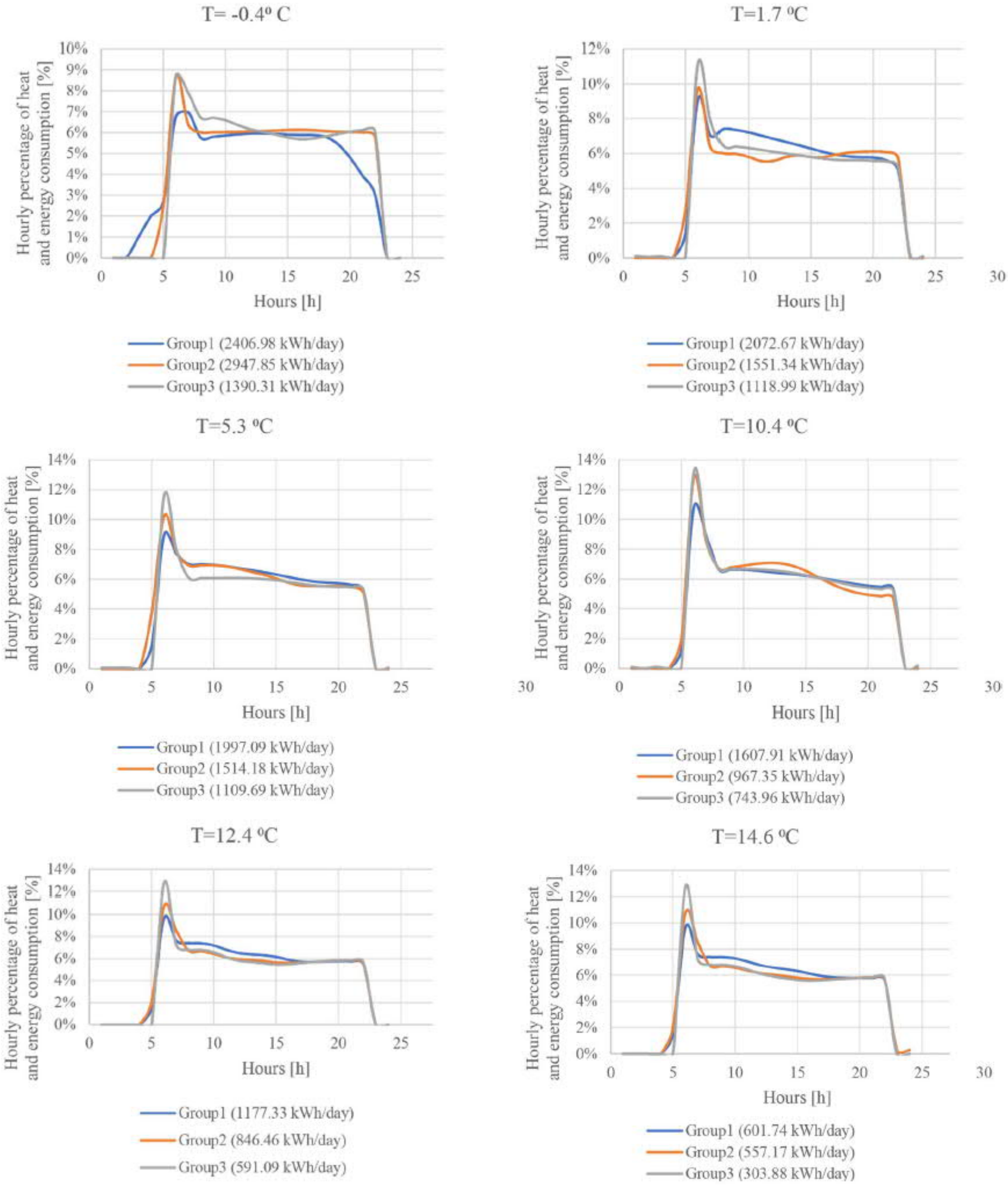


Figure 32: Daily heating consumption profiles of office buildings for different outdoor temperatures [189].

5.4.2 Domestic hot water

Compared to the heating energy consumption of space heating and ventilation air, the consumption of DHW is less dependent on the outdoor temperature. As a result, DHW consumption tends to fluctuate less with the change of seasons. Fuentes et al. performed a review on the existing literature on the DHW consumption patterns [194]. The monthly, weekly and daily DHW usage patterns are shown in Figures 33-35. The data was obtained from: [185],[195]-[198] for the monthly consumption patterns,

[184],[196],[197] for the weekly consumption patterns and from [199]-[202] for the daily consumption patterns.

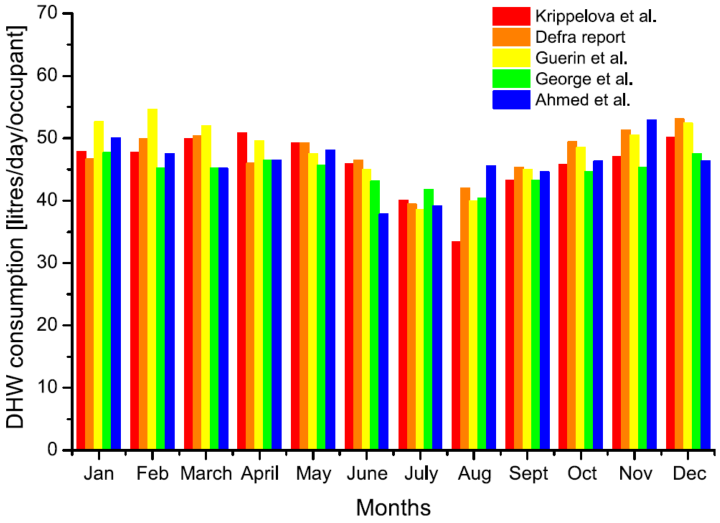


Figure 33: Monthly DHW consumption profiles of residential buildings [194].

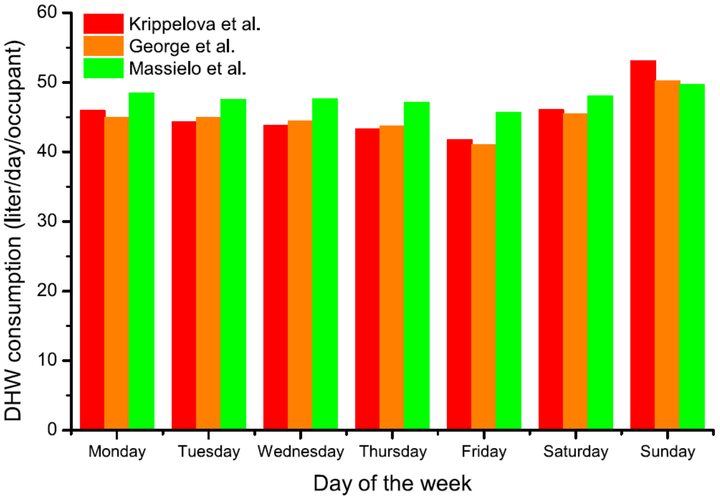


Figure 34: Weekly DHW consumption profiles of residential buildings [194].

Figure 33 shows the monthly DHW consumption in residential buildings [194]. As can be seen, the consumption of DHW does decrease during the summer months, though the difference in consumption between summer and winter months is only around 20%. Weekly DHW consumption in residential buildings is shown in Figure 34 [194]. The consumption of DHW is higher during the weekend compared to the weekdays. This is likely due to the increased occupancy during the weekends. Furthermore, the timing of the morning consumption peak is delayed during the weekends. On weekdays, the DHW consumption tends to peak once at around 8 AM and a second time in the evening [196]. On Saturdays and Sundays, the morning peak is delayed to around 2 PM, though the evening peak is similar to that of weekdays [196]. The daily load profile of DHW for different building types is shown in Figure 35 [194].

Similarly to household electrical appliances, the use DHW in residential buildings is largely dictated by the usual human diurnal rhythm. The morning and evening consumption peaks can be clearly seen in the data for residential buildings. Offices and hotels have similarly shaped load profiles, with a small peak in the morning and a larger peak later in the afternoon or evening. This is likely due to the similar hours of occupancy between these buildings and residential buildings. For restaurants, the two consumption peaks taking place in the afternoon and in the evening are likely associated with lunch and dinner times, respectively.

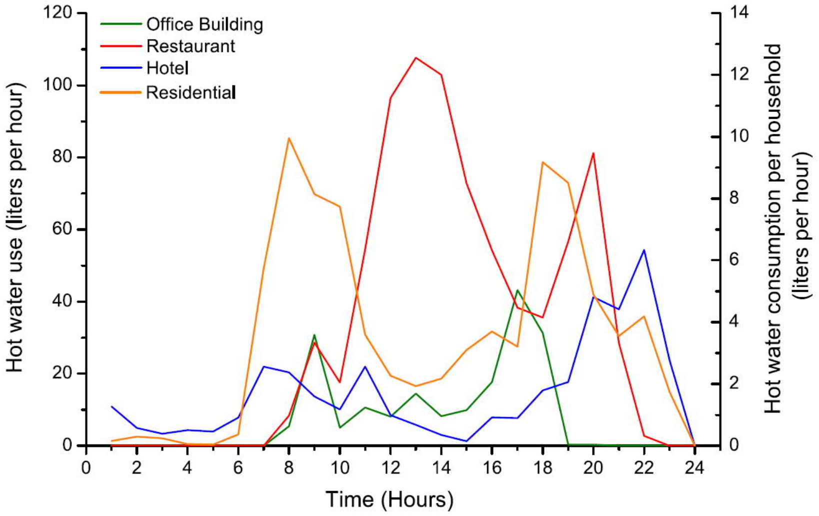


Figure 35: Daily DHW consumption profiles of different building types [194].

6 Demand response

This chapter elaborates on the concept of demand response. DR is a subset of demand-side management measures, which focus on altering customer energy consumption to better match the energy generation [10]. From the perspective of the power system, the emphasis of DR is on increasing the system flexibility [13],[203].

The US Department of Energy defines DR as follows: “Demand response is a tariff or program established to motivate changes in electric use by end-use customers in response to changes in the price of electricity over time, or to give incentive payments designed to induce lower electricity use at times of high market prices or when grid reliability is jeopardized” [203]. As such, DR programs can be classified into price-based and incentive-based programs.

This chapter is structured as follows. Section 6.1 discusses the different load shaping objectives that can be accomplished using DR. In Section 6.2, price-based and incentive-based DR programs are introduced. And lastly, Section 6.3 focuses on comparing the different DR programs.

6.1 Load shape objectives

DSM can be used to influence the patterns and magnitude of the end-use consumption in various ways. The effects of DSM on the shape of the load curve can be categorized into reducing, increasing and rescheduling. [6] The range of possibilities is usually illustrated by the following six different load shaping objectives (Figure 36) [6],[203]-[208]:

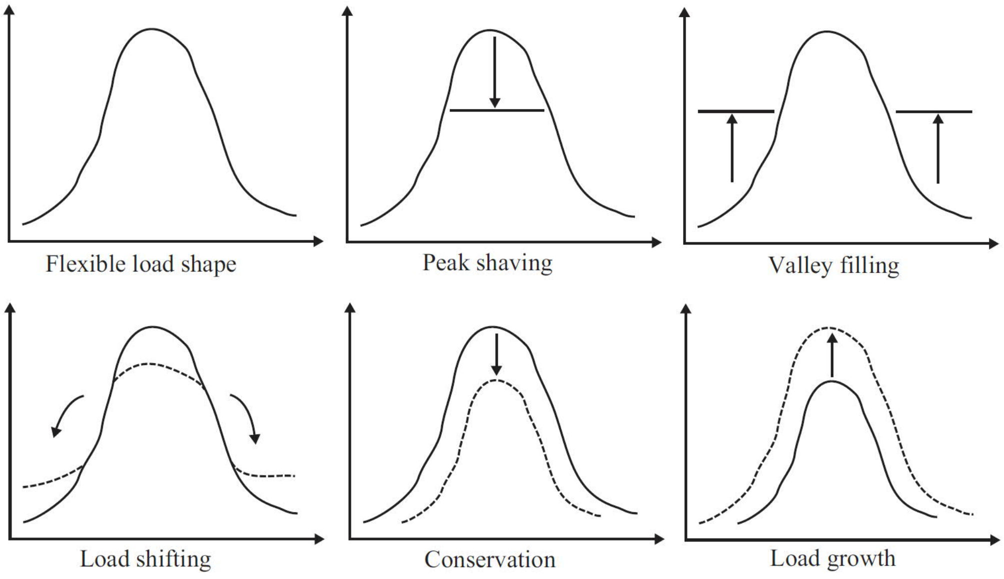


Figure 36: DSM load shape objectives [6].

Flexible load shape allows the utility to alter customer energy consumption when necessary. Instead of permanently influencing the load shape, customer loads are interrupted on an as-needed basis.

Peak shaving refers to the reduction of energy consumption during peak demand periods. Peak shaving causes reduction in both the peak demand and the total energy consumption.

Valley filling involves building the load during the off-peak periods. This is often desirable when there is underutilized capacity that can operate on low cost. The net effect of valley filling is an increase in total energy consumption but not in peak demand.

Load shifting refers to shifting consumption from the peak demand periods to off-peak periods. As a result, peak demand is reduced without affecting the total energy consumption.

Conservation entails reductions in the end-use consumption during all or most hours of the day, leading to reductions in both the peak demand and the total energy consumption.

Load growth (or load building) involves an increase in the overall energy consumption, leading to greater peak demand and total energy consumption.

Of the load shaping objectives mentioned above, DR can be used to implement flexible load shape, peak shaving, valley filling and load shifting. Load shifting is beneficial compared to the other load shape objectives, as it enables system flexibility without affecting the continuity or the quality of service [6]. Conservation is implemented through improvements in the end-use energy efficiency, whereas load growth requires an increase in energy intensity or the addition of new customers. Therefore, these two objectives cannot be implemented via DR measures alone.

6.2 DR programs

This section introduces the most commonly employed DR programs. Multiple different ways of classifying DR programs exist and DR program categories are often given different names such as: names such as “system- and market led”, “emergency- and economic-based”, “price- and dispatch based” can be found in the literature [8],[209],[210]. In this thesis, DR programs are divided into price-based and incentive-based programs. A further breakdown of these categories is shown in Figure 37 [168],[211].

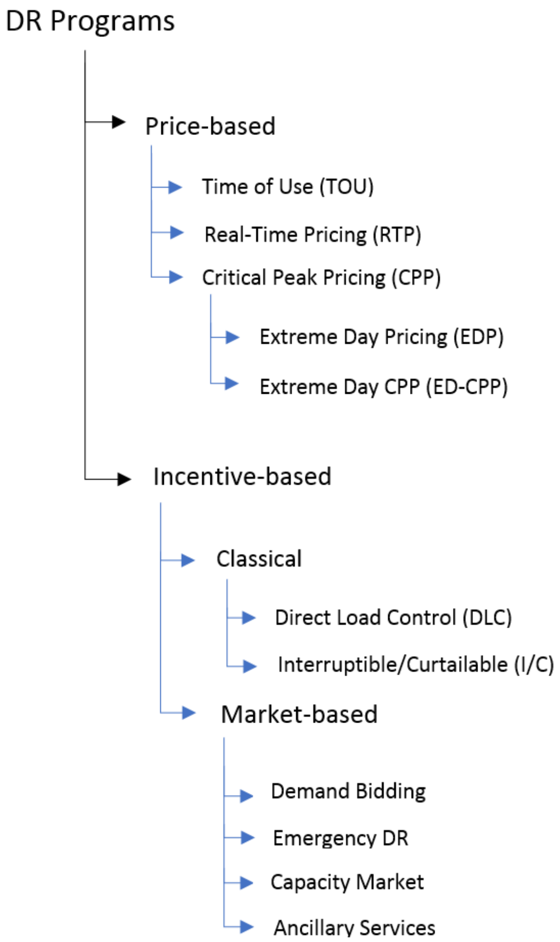


Figure 37: Classification of DR programs.

6.2.1 Price-based programs

Price-based DR programs are based on changes in energy consumption by customers in response to changes in energy prices. The energy price per unit consumption is higher during the peak demand periods compared to the off-peak periods. Customers can voluntarily adjust the timing of their consumption to take advantage of the lower-priced periods or avoid consuming when prices are higher. The fundamental goal of price-based DR programs is to flatten the demand curve by encouraging consumption during the off-peak hours and disincentivizing consumption during the peak hours. Price-based programs can be divided into three categories: Time of Use (TOU), Real-Time Pricing (RTP) and Critical Peak Pricing (CPP). [203],[211]

In TOU programs, the pricing of energy follows a schedule where different prices are used during different periods of the day. An example of TOU program is having a higher price for energy during the day compared to night. This type of pricing is common in Europe. In RTP programs, customers are charged fluctuating prices based on the real cost of energy in the wholesale market. Customers are typically notified of energy prices on day-ahead or hour-ahead basis. CPP programs are a mix of TOU and RTP program designs. In CPP, the base energy price is based on TOU, however, if a specified trigger condition is met, a significantly higher CPP event price replaces the normal peak price.

Extreme Day Pricing (EDP) and Extreme Day CPP (ED-CPP) are subcategories of CPP programs. In EDP, the higher energy price is in effect the whole 24 hours of the extreme day. In ED-CPP, CPP pricing is used during extreme days, but flat pricing is used for the other days. [8],[203],[211]

6.2.2 Incentive-based programs

Incentive-based programs offer customers monetary incentives that are separate from, or additional to, their retail energy price. These incentives can be time-varying or fixed. In incentive-based programs, customers usually sign contracts with utilities, load-serving entities or regional grid operators. The program coordinator may request load reductions from the customers when the grid reliability conditions are compromised or when the energy price is too high. Incentive-based programs can be divided into classical and market-based programs. [203],[211]

Classical programs can be further divided into Direct Load Control (DLC) programs and Interruptible/Curtailable (I/C) programs. In DLC programs, the program operator can remotely shut down or cycle participant loads on a short notice. I/C programs offer the participants rate discounts or payments for agreeing to reduce loads during system contingencies. Penalties may be imposed on participants who fail to curtail when asked, depending on the program conditions. [211] DLC programs are typically offered to residential and small commercial consumers, whereas I/C programs are offered only to large industrial consumers. [203]

In Market-based programs, participants are monetarily rewarded depending on the amount of load reduction during critical conditions. Market-based programs are divided into Demand Bidding, Emergency DR, Capacity Market and Ancillary Services Market programs. In Demand Bidding, customers offer bids to specific load reductions on the wholesale market. If a bid is accepted, the customer must reduce load by the specified amount. Penalties are imposed on customers who fail to curtail. Emergency DR programs offer payments to customers for measured load reductions during critical conditions. Capacity Market program participants can offer load reductions to replace conventional generation when system contingencies arise. In turn, participants receive reservation payments, and face penalties for failing to reduce load when called upon to do so. In Ancillary Services Market programs, participants bid load reductions as operating reserves. If a bid is accepted, participants are paid the market price for committing to be on standby and if their load curtailments are needed, they are paid the spot market price. [8],[203],[211]

6.3 Comparison of DR programs

In this section, different DR programs are compared in terms of both the customer inconvenience and the characteristics of the achieved load reductions. These two factors largely affect the amount of flexibility that can be achieved with DR [6],[15]. The use of automated control technologies for price-based and market-based DR programs are not considered here, though automation may be an efficient way to optimize the performance of these programs [212].

6.3.1 Customer inconvenience

The flexibility potential of residential and service buildings is largely determined by the willingness of customers to participate in DR programs. The inconvenience caused by the control of a load affects customers' willingness to accept compensation for the control of said load [15]. Moreover, customers tend to be less willing to shift or curtail loads they consider to be critical to them [16].

DR programs may cause two types of inconvenience to customers: inconvenience associated with the act of participating in the program and inconvenience associated with the consequences of the load control. Consequences of the load control include restriction of leisure activities and work performance, compromised comfort levels, data loss and reconfiguration of equipment, and food spoilage [16]. The inconveniences associated with the participation differ between DR programs. In price-based programs, the customer has to follow the energy prices and take into account their own short- and long-term decisions [8]. In market-based programs, the customer must directly participate in the energy market, which may be both difficult and time consuming. Moreover, the market outcomes may be undesirable to the customer [8]. An advantage of price- and market-based DR programs is that they offer customers the choice of when to participate. On the other hand, DLC programs require little or no action from the customer. However, DLC programs offer the customer no real-time choice of when to participate and program coordinators may require access to information about energy consumption, which some customers may consider a privacy issue. [8]

6.3.2 Load reduction

Load reductions achieved by different DR programs may differ in terms of magnitude and reliability [8]. The magnitude of load reduction is highly dependent on the number of customers participating in the program [14]. DR programs with low entry barriers are likely to have higher participation rates compared to programs with high entry barriers. Such barriers may include the costs of participating and the uncertainties of the benefits. [203] The reliability of the load reduction depends mostly on which party is responsible for initiating the load reduction response [8].

The barrier for entry is likely lower for price-based DR programs than for incentive-based programs [203],[212]. The actual amount of load reduction can be significantly lower than the amount of enrolled commitments. For example, [212] found that the average load reduction achieved with an RTP program can be as low as 21% of the total enrolled capacity. Moreover, the load reductions achieved with price- and market-based DR programs are inherently unpredictable. Consumers may not act as expected as they do not necessarily act to maximize their own economic benefit [8]. Indeed, various cognitive and decision-making biases may lead to customers acting irrationally (in an economic sense) [213]. Moreover, customers may not respond to prices quickly, leading to potential delays in load reduction. In the worst-case scenario, too many load responses to the same price signals may result in power oscillation, leading to power system instability. [8]

DLC programs offer the utility more control over the enrolled loads and therefore ensure reliable and predictable load reductions [8]. Another benefit of DLC is that the response times are fast: load reductions can be deployed within minutes, without having to wait for a customer response [212]. However, the barrier for entry is higher for DLC programs, since they involve installation of control equipment and are likelier to raise privacy concerns [8],[14]. In addition, consumers may feel distrust toward the utility, leading to decreased willingness to participate in DLC [14].

7 Flexibility evaluation of building loads

In this chapter, a qualitative evaluation is performed on the electrical and thermal loads of residential and service buildings, based on the findings of the previous chapters. Magnitude of energy consumption, timing of the consumption relative to peak demand periods, user inconvenience and the suitability for an existing DR program will be considered in the evaluation. In this thesis, peak demand periods are defined as the hours between 7 AM and 10 AM and the hours between 4 PM and 10 PM. The aim of this chapter is to identify the electrical and thermal loads that are best suited to be included in a DR portfolio.

7.1 Electrical loads

7.1.1 Air conditioning

Even though household AC ownership is still fairly low in many parts of the world, AC does represent a significant portion of electricity consumption in households that do own an AC. In most service buildings, AC is the single largest electrical load, often accounting for up to 50% of the total electricity consumption. Moreover, the effect of AC on electricity peak demand is particularly significant: its share of peak electricity demand is often twice as high as its share of total electricity demand. Therefore, AC is a prime candidate for DR measures, especially in service buildings.

Due to the low thermal inertia of indoor air, long-term load shifting with the use of pre-cooling is likely not an efficient option, due to the adverse effects on customer thermal comfort. Therefore, peak shaving and short-term load shifting are the most likely load shape objective achieved with the DR of AC. In the short to medium-term, load shifting could be achieved via DLC: [16] showed that 50% of residential customers were willing to shift their AC usage for 60 minutes. Price-based DR programs, such as RTP and CPP, are another potential option. One way to implement price-based control is via the combination of automatic or manual user control and thermostatic boundary conditions [214],[215]. The AC load can respond to the price signals whilst ensuring thermal comfort of the customer.

7.1.2 Lighting

At electricity consumption shares of 10 – 20% for residential and 12 – 40% for service buildings, lighting is another electrical load that contributes significantly to the electricity consumption in most types of buildings. The timing of consumption of building lighting systems is mostly dependent on the building occupancy. Therefore, lighting systems of buildings that are occupied during the peak demand periods are likely more significant contributors to peak electricity consumption. These buildings include residential buildings, hotels, and wholesale and retail trade buildings.

Lighting is a curtailable load, but not a shiftable load: the value lost due to an interruption in lighting cannot be regained by switching the lights on later. As a result, peak shaving is the only load shaping objective that can be achieved with controlling of lighting loads. In order to ensure that the customer minimum illuminance requirements are not violated, dimming and partial load shedding could be utilized [216]. This type of lighting control requires centrally controlled luminaires and smart metering, possibly resulting in a higher barrier of entry for residential customers. However, it has been shown that lighting systems have the highest elasticity out of all household electrical loads in so suggesting that residential customers may be willing to reduce lighting loads for minimal compensation [217]. In RTP or CPP programs, lighting loads could respond to price signals, either manually or automatically, depending on whether smart metering is utilized.

7.1.3 Cold appliances

Cold appliances contribute significantly to the electricity consumption in very few building types, namely in residential buildings and wholesale and retail trade buildings. Convenience stores and smaller markets are particularly energy intensive in terms of the electricity consumption of cold appliance, due to the large proportion of floor space dedicated to frozen and chilled food products. Cold appliances consume electricity in a continuous, cyclic fashion. There are no clear daily peaks in the electricity consumption of cold appliances, since the consumption is dependent mostly on outside temperature.

The use of cold appliances as a part of DR is largely limited by their thermal inertia. For cold appliances used in food retailing, the food delivery periods and peak sale periods impose some additional constraints for the load reduction periods [141]. Moreover, since cold appliances are usually thermostatically controlled, load shifting is the only conceivable load shape objective.

Poorly insulated cold appliances, like refrigeration display cabinets, are suited only for short-term load control (from seconds to few minutes). These types of cold appliances are mostly used in food retail stores. DR of these types of cold appliances may be suitable for applications such as power system frequency stabilization [6],[218]. Medium-term load reductions (up to one hour) could likely be achieved in well insulated appliances, such as glass-doored freezers and chest freezers. These cold appliances are in food retail use as well as in household use, making residential buildings and food retail buildings prime candidates for DR of cold appliances. DLC is likely the best option for implementation of DR of cold appliances, and it is the most widely studied option in the current literature [93],[141],[218].

7.1.4 Active appliances

Active appliances include cooking appliances as well as LDC appliances. When it comes to these appliances, the current literature focuses mostly on residential households [6],[13]. Indeed, active appliances account for a significant portion of residential building electricity consumption: around 14% of total electricity consumption for both cooking appliances and LDC appliances. Whereas LDC appliance are mostly used in residential buildings, the electricity consumption share of cooking appliances can be very high in service buildings equipped with catering services. These buildings include for example hotels and hospitals. However, it is reasonable to assume that DR of active appliances would likely be limited to residential appliances. This is because, in order to achieve load reductions in commercial active appliances, a disproportionate amount of incentives would be needed to cover the costs of lost business.

Due to their high power draw and time of usage, household active appliances can contribute substantially to peak electricity demand. Cooking appliances tend be more significant, since their use tends occur mostly between 5 PM and 8 PM. LDC appliances tend to contribute less to peak demand, as their use is spread more evenly throughout the day.

Since active appliances are mostly used to serve basic human needs, these loads cannot be curtailed. Therefore, load shifting is the main load shape objective achieved via control of active appliances. Cooking appliances are likely well suited for medium-term load reductions, as it has been shown that customers' willingness to shift the use these appliances is fairly high up to one hour, but quickly falls of for longer durations [16]. LDC appliances are well suited for longer load reduction durations (up to 10 hours), as customers tend to willing to shift the use of these appliances for long periods [16]. Active appliances are well suited for both price-based and DLC programs. As customers to view LDC appliances as less critical, LDC appliances are likely better suited for DLC than cooking appliances.

7.1.5 Continuous and standby appliances

Continuous appliances are those that continuously consume a constant amount of electricity. Continuous appliances do not contribute significantly to the electricity consumption in any type of building, and due to their constant and low power draw, their effect on peak demand is insignificant. It is unlikely that these appliances would be well suited for DR.

Standby appliances have three modes of operation: on, off and standby. Standby appliances include ICT and audiovisual appliances. ICT appliances account for a significant portion of the total electricity consumption in office and educational buildings. The electricity consumption share of ICT appliances is moderate in residential buildings, hotels and hospitals. The use of ICT appliances is spread evenly throughout the day in residential buildings. Furthermore, ICT appliance usage in offices and educational buildings can be assumed to happen during hours of occupancy, which for these buildings is mostly during off-peak hours. Therefore, ICT appliances are not particularly significant contributors to peak electricity demand. Audiovisual appliances are used almost exclusively in residential buildings, where they account for about 14% of total electricity consumption. Household audiovisual appliances tend to be used more extensively during the evening, making them one of the largest contributors to residential building peak demand, along with cooking appliances and lighting.

The use of office and educational building ICT appliances in DR programs faces the same problem as the use of catering service cooking appliances: ICT appliances are essential for the work in these buildings and the DR of ICT appliances would impair work productivity and thus cause monetary losses. In residential buildings, ICT and audiovisual appliances are the two appliance groups whose use customers are least willing to shift [16]. Therefore, the amount of flexibility achieved via DR of standby appliances is likely low. Short-term load shifting could potentially be achieved, perhaps with the use price-based DR programs. Longer load shifting durations and the use of DLC would likely cause excessive inconvenience, as residential customers tend consider these appliances as critical.

7.2 Thermal loads

7.2.1 Space heating and heating of ventilation air

Majority of the heating energy consumed in buildings is used for space heating and the heating of the ventilation air. Space heating accounts for between 45% and 60% of the total heating consumption. Usually between 25% and 35% of the heating energy consumed is used for heating the ventilation air, though this number can be significantly less in buildings with efficient exhaust air heat recovery systems. Residential buildings, hospitals, and wholesale and retail trade buildings tend to have the largest heating EUIs.

Outdoor temperature is the single largest predictor of heating energy consumption of these thermal loads. Other variables affecting the heating consumption include building physical characteristics, occupant behavior, building ventilation rate and the type of heating system used. Some evidence suggests that occupant behavior has a relatively larger effect on heating consumption in newer buildings compared to older buildings. Buildings that use DH for heating tend to have larger heating EUIs than buildings that use electric heating systems. There may be differences in heating consumption between radiator systems and floor heating systems. However, there seems to be no clear consensus in the current literature on which of the systems is more energy intensive. Furthermore, building heating consumption seems to increase close to linearly with ventilation rate.

Load reductions in space heating and heating of ventilation air can be achieved only during the heating season, which in Finland is the period during which average outdoor temperature is below 17 °C. These thermal loads are shiftable but likely not curtailable, as customer thermal comfort must be guaranteed. Depending on the building’s thermal inertia, load reduction durations of up to several hours could likely be achieved.

Buildings with large thermal inertias are well suited for DR, as they tend conserve the occupant thermal comfort effectively during a period of no heating. Buildings with floor heating systems have larger thermal inertias compared to buildings with radiator systems. Moreover, hydronic heating systems likely have larger thermal inertias than their direct electric counterparts. High ventilation rates tend to decrease thermal inertia and it may be possible to achieve longer load reduction durations by decreasing the ventilation rate during the load shift period. This could be applicable particularly in office buildings as they tend to have ventilation rates well above the guideline value. Another way to potentially increase the load reduction duration is by overheating the building prior to the load shift period. Though it is worth mentioning that this may significantly increase the total heating consumption of the building [132].

Buildings that utilize DH as their heating method are well suited for DR, as buildings with hydronic heating systems tend to have high thermal inertias. In addition, the thermal inertia of the DH network can be utilized in conjunction with the thermal inertia of the buildings. In the case of Finland, these buildings include residential apartment buildings, offices and wholesale and retail trade buildings. When considering load reduction durations, it may be worth considering the proximity of the building to the DH plant, since buildings in the peripheries of the network may experience larger reductions in indoor temperature. Buildings with electric heating systems can be utilized for DR regardless of location, though load reduction durations would likely have to be shorter if DEH is utilized. In Finland, detached houses commonly utilize electric heating. DLC is well suited for the control of space heating and heating of ventilation air. This is because customers are primarily concerned about their thermal comfort and not about whether heating energy is currently being provided. Lastly, in order to prevent the formation of new heating consumption peaks, attention must be paid to the rebounding behavior observed in thermal loads after being switched back on after a load reduction period.

7.2.2 Domestic hot water

Residential buildings are the single largest consumer of domestic hot water: households account for over 70% of total DHW consumption. The share of DHW of household total heating consumption is between 15% and 20%. Small households tend to consume more DHW per person compared to larger households. Some service buildings, like hospitals and hotels, can have high DHW EUIs. However, DR of DHW is likely not a viable option in these buildings, due to the potential for large inconveniences and monetary losses.

Compared to space heating, the consumption of DHW is less dependent on the outdoor temperature. DHW consumption is only around 20% lower during the summer months, compared to the heating season. Therefore, DHW can potentially be utilized in DR regardless of the times of the year. There are two distinct peaks in residential DHW usage: one in the morning and one later in the evening. In terms of total heating energy peak demand, the morning peak in DHW usage is more significant, since it coincides with the space heating morning peak. Therefore, it may be particularly impactful to shift the heating energy use associated with DHW away from the morning peak.

DR of DHW is limited by the thermal comfort requirements of the customers. Since thermal comfort must be maintained, load shifting is the only conceivable load shape objective achieved with DR of DHW. In addition, the temperature of the hot water circuit must be kept above a certain limit in order to prevent the growth of Legionella bacteria. In Finland, this limit is set to 55 °C by the Ministry of Environment [219]. Therefore, DR of DHW in buildings utilizing DH is likely limited to medium-term load reductions. Longer load reductions could potentially be achieved in buildings utilizing electric heating, as these buildings often have hot water storages. DLC is likely a suitable option for control of DHW, as thermal comfort is the primary customer concern and not the DHW supply itself.

8 Conclusions

This thesis evaluated the flexibility potential of building electrical and thermal loads. This was achieved by conducting a comprehensive literature review on the energy consumption of both residential and service buildings. Based on the findings of the literature review, a qualitative analysis of the building loads was carried out. The following factors were considered in the analysis: the magnitude of energy consumption, timing of consumption relative to peak demand periods, consumer inconvenience and the suitability for an existing DR program.

In residential buildings, differences in electricity consumption between households are mostly due to differences in appliance ownership and energy efficiency. The most energy consuming electrical loads in residential buildings are lighting, cold appliances, cooking appliances and audiovisual appliances. Small households tend to consume more electricity per person compared to larger households. Outdoor temperature is the largest predictor of building heating consumption. Other factors include building physical characteristics, ventilation rate, heating system type and occupant behavior. Using DH over electric heating, high ventilation rate, and small household size were factors associated with higher building heating EUI.

In terms of energy consumption, service buildings are a much more heterogeneous group compared to residential buildings. Energy consumption of service buildings can differ significantly between building types as well as between buildings of the same type. Out of the buildings examined in this thesis, education buildings had the lowest EUIs, whereas wholesale and retail trade buildings had the highest. AC was identified as the single largest electrical load in most types of service buildings, apart from food retail stores, where cold appliances account for most of the electricity consumption. Lighting was generally the second largest electrical load. In terms of heating consumption, the differences between building types were not as significant. Hospitals and wholesale and retail trade buildings had the highest heating EUIs. Heating consumptions of offices, hotels and educational buildings were similar to residential buildings.

Service building AC was identified as perhaps the most promising source of flexibility: AC often accounts for as much as 50% of the total electricity consumption in service buildings and its effect on peak demand is even greater. Cold appliances are another potentially significant source of flexibility. Well insulated cold appliances in residential buildings and food retail stores could likely be used for DR without any inconvenience to the customers. However, load reduction duration of cold appliances is limited by the potential for food spoilage. DR of active appliances is probably limited to those in residential buildings. Flexibility can be found in cooking appliances as well as in LDC appliances. Cooking appliances are better suited for shorter load reduction durations, whereas the use of LDC appliances can be shifted for longer periods. Residential and service building lighting may provide some flexibility, though in order to realize the full flexibility potential of lighting, dimmable luminaries and smart metering may be needed.

The flexibility analysis carried out in this thesis was mostly based on qualitative features of the examined building electrical and thermal loads, and therefore magnitudes of available total load flexibilities cannot necessarily be inferred from the results. The number of different building types available for DR and the actual customer participation rates need to be considered as well. Moreover, the suitability of building loads for DR was mostly considered from the point of view of the customer. Therefore, more studies investigating the relationship between estimated and actual available flexibility of different building loads are needed. Furthermore, in order to gain a realistic view of the flexibility of building electrical and thermal loads, the point of view of the service provider must be considered.

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