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Forecasting and modeling energy consumption of hospital buildings

Relation between energy consumption, architectural features as morphology, layout and medical functions

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Abbreviations

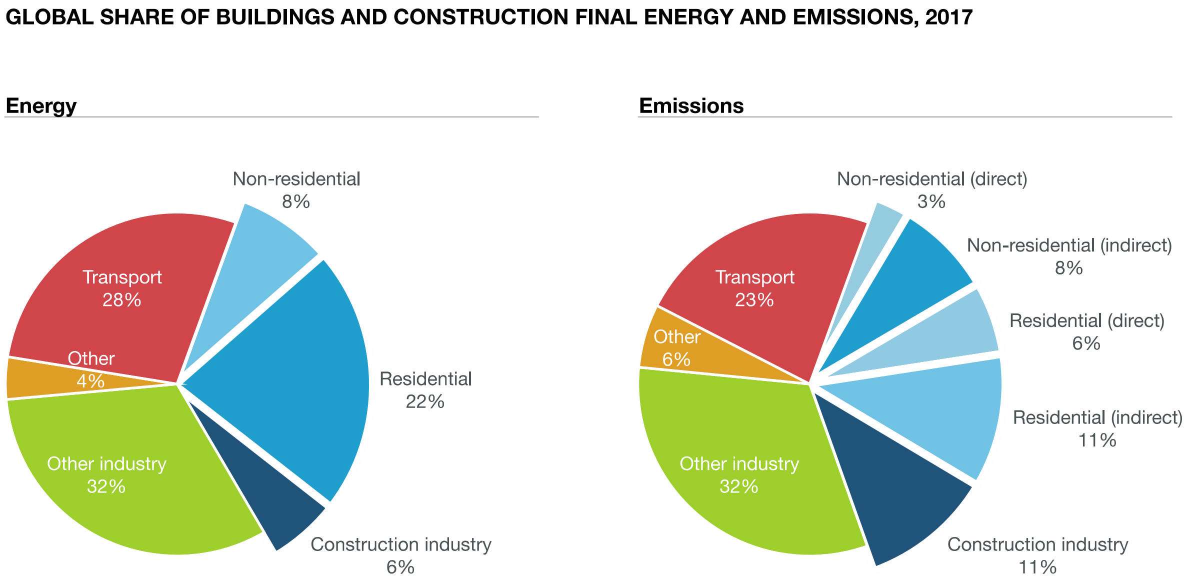
AEDG	Advanced Energy Design Guide
A&E	Accident and Emergency
AHU	Air handling unit
D&T	Diagnostic and Treatment facilities
DHW	Domestic hot water
EUI	Energy Use Intensity
FA	Functional area
GDP	Gross domestic product
GHG	Greenhouse gas
HVAC	heating, ventilating and air conditioning
IDL	Integrated Design Lab
IPUs	Inpatient Units
LPDs	lighting power densities
OPD	Outpatient Department
OR	Operating room
PPLs	Plug and process loads
SWH	Service water heating
TSDs	Technical Support Documents

1 Introduction

In 2018 global energy demand and carbon emissions from energy use grew at a rate of 2.9%, almost double its 10-year average and the fastest since 2010, moving even further away from the accelerated transition envisaged by the Paris climate goals. The strength in energy consumption was reflected across all the fuels, most of which grew more strongly than their historical averages. This acceleration was particularly driven by natural gas, which rose by 5.3%, one of its strongest growth rates for over 30 years, accounting for almost 45% of the total increase in global energy consumption.

Against this background, the buildings and construction sector accounts for 36% of global final energy consumption and about 40% of energy-related CO2 emissions, nearly one third of this is due to non-residential buildings (IEA, 2018a) (Figure 1.1). Furthermore, energy demand from buildings and construction continues to rise at nearly 3% per year, driven by improved access to energy in developing countries, rapid growth in global buildings floor area and greater ownership and use of energy-consuming devices (IEA, 2019). Final energy use in buildings grew from 2820 million tonnes of oil equivalent (Mtoe) in 2010 to around 3060 Mtoe in 2018 (about 8,5%), with the impact from the growth in floor area and population outpacing the impact of energy efficiency improvements (IEA, 2018b).

When indirect emissions from upstream power generation are considered, buildings were responsible for 28% of global energy-related CO2 emissions in 2018. In absolute terms, buildings-related CO2 emissions rose for the second year in a row to an all-time high of 9.6 GtCO2. This resulted from several factors, including extreme weather that raised energy demand for heating and cooling (IEA, 2018c).



Note: *Construction industry* is an estimate of the portion of the overall industry sector that applies to the manufacture of materials for buildings construction, such as steel, cement and glass.

Figure 1.1. Global share of buildings and construction final energy and emissions, 2017.
Sources: IEA, 2018a and IEA, 2018c.

1.1 Hospital energy consumption and carbon footprint

Whilst accounting for about 7% of the total built area within the EU non-residential sector (6.5% in Italy), hospitals present the highest energy consumption per unit floor area (EC, 2018). They contribute 10% of the total energy use (BPIE, 2011) and are estimated to be responsible for roughly 5% of the EU carbon dioxide emissions (LCB Healthcare, 2011). In OECD countries healthcare on average accounts for about 5% of the national CO2 footprint, reaching 10% in the U.S. (Eckelman, 2016), 3% in England (NHS Sustainable Development Unit, 2016) - where it is equivalent to 30% of UK total public sector carbon emissions (NHS Sustainable Development Unit, 2010) - 7% in Australia (Malik et al., 2018) and 5% in Italy (Pichler et al., 2019), as reported in Figure 1.2.

HEALTH CARBON FOOTPRINT (HCF) AS PERCENTAGE OF NATIONAL CARBON FOOTPRINT (CF)

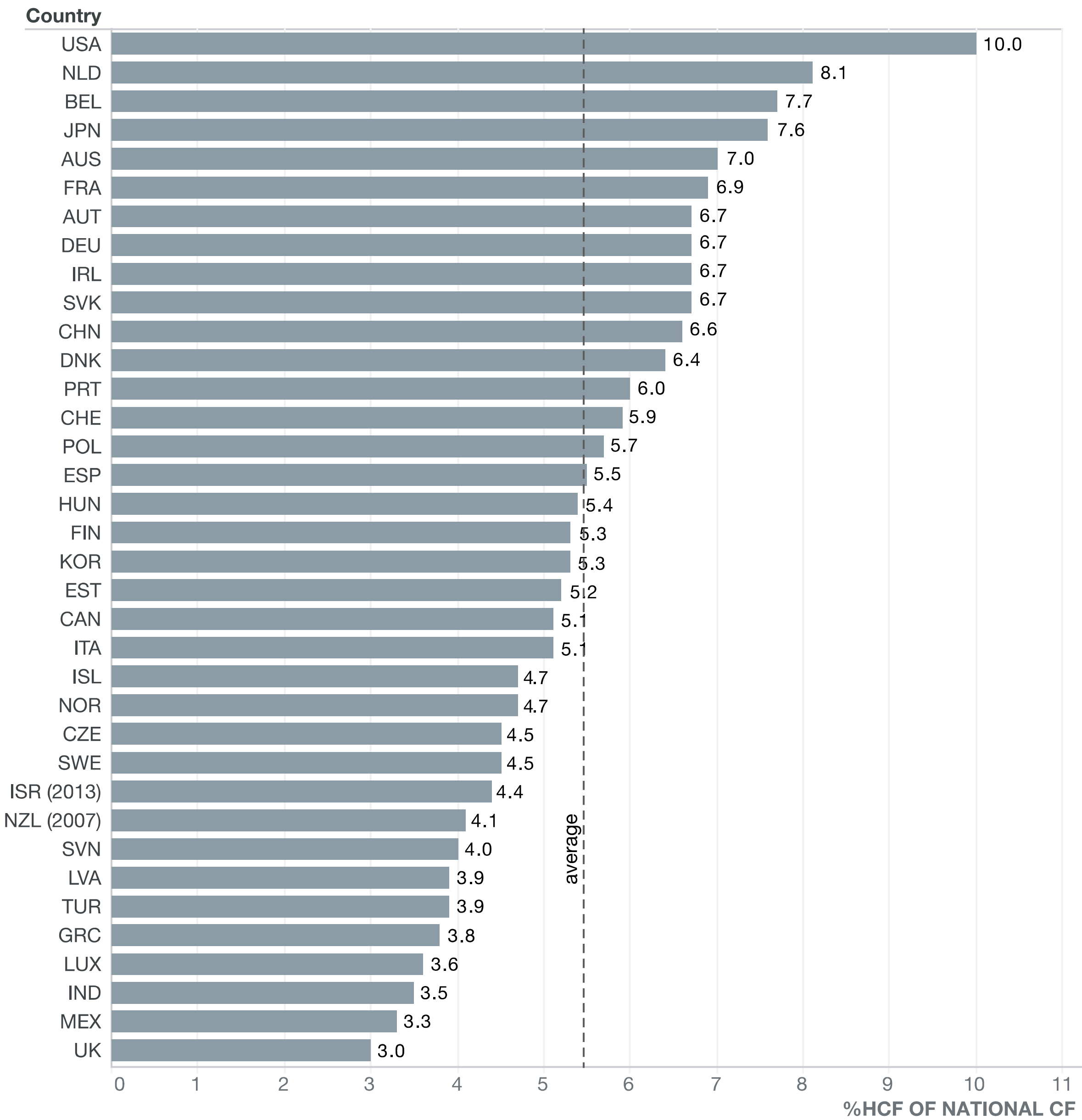


Figure 1.2. Health carbon footprints (HCF) as percentage of national carbon footprint (CF). Based on Eckelman, 2016, Malik et al., 2018, NHS Sustainable Development Unit, 2016 and Pichler et al., 2019 data. All rights reserved; as modified by the author.

Due to the difference in greenhouse gas (GHG) conversion factors (GOV.UK, 2018a) reported in Table 1.1, the amount of carbon released during the process of electricity generation is decisively higher than the one related to natural gas, as outlined in Figure 1.3.

Table 1.1. GHG conversion factors 2018

Fuel	kgCO2e per kWh*
Electricity	0.28
Gas	0.18
Oil	0.26
Coal	0.31

* kilograms carbon dioxide equivalent (kgCO2e) per unit of fuel

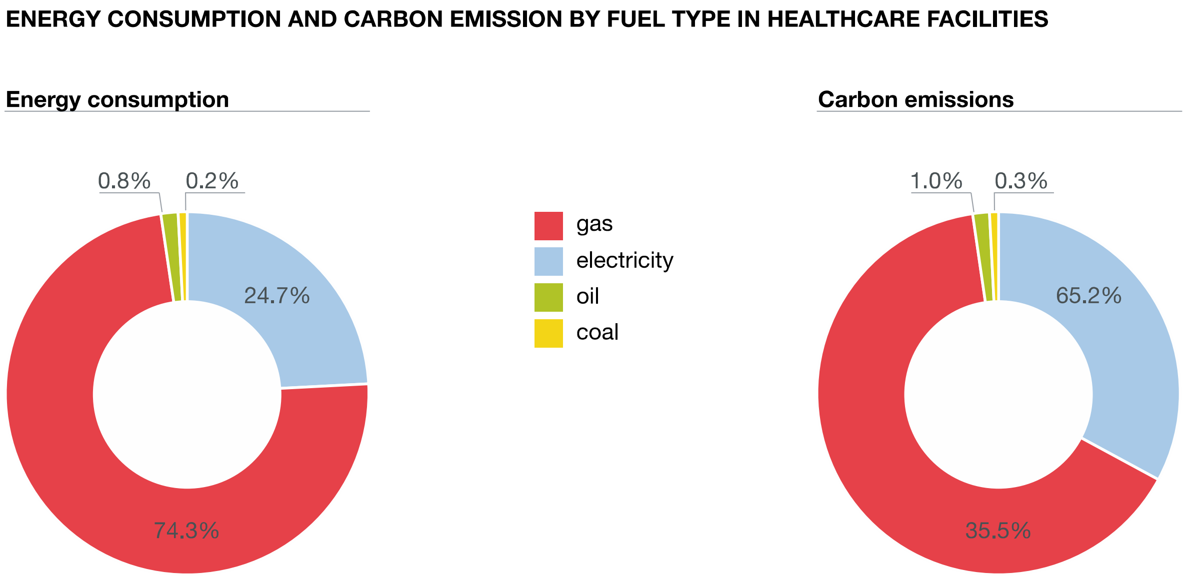


Figure 1.3. Energy consumption and carbon emissions by fuel type for healthcare facilities in 2017-2018. Based on GOV.UK (2018a) and NHS Digital (2018) data. All rights reserved; as modified by the author.

This is a very significant issue for the healthcare sector, where electricity consumption is rising rapidly because of the growth in the use of information technology (IT), medical equipment and air conditioning. This is a greater issue for new buildings, where space heating demand is expected to decrease as a result of improved thermal performance, while electricity requirements remain the same or even increase. This is illustrated in Figure 1.4, where a decrease of fossil fuels is observed, as opposed to the almost stable electricity use (NHS Digital, 2018).

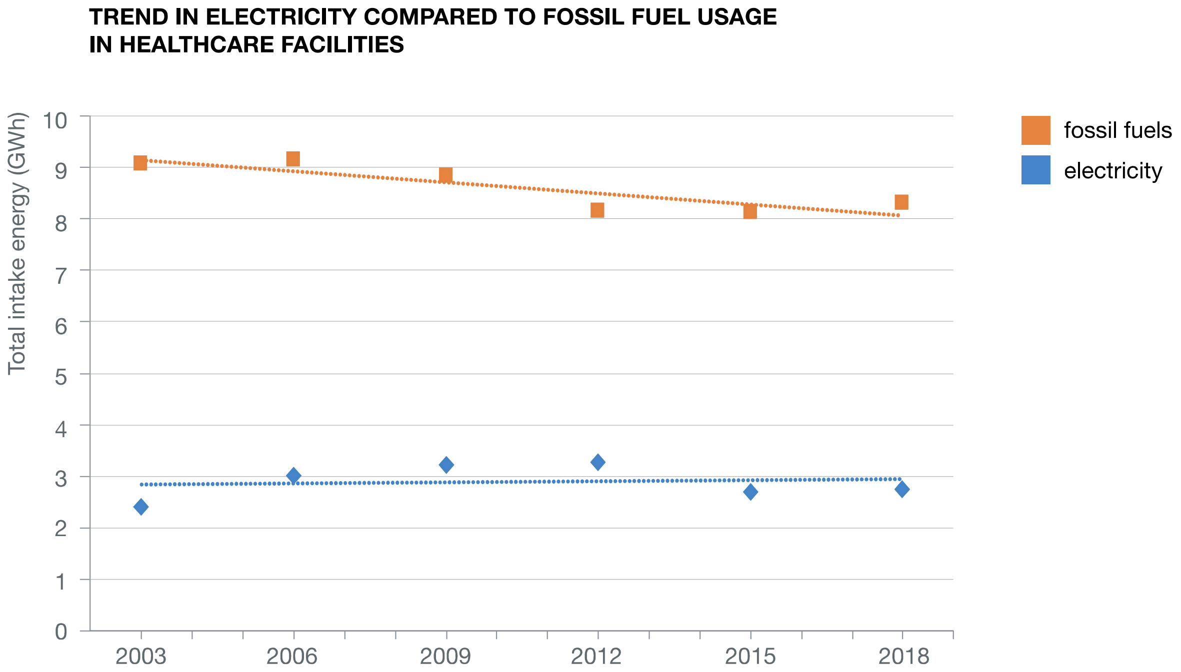


Figure 1.4. Trend in electricity growth compared to fossil fuel usage in healthcare facilities. Based on NHS Digital (2018) data. All rights reserved; as modified by the author.

Therefore, while they should be designed to improve public health and respect the environment, hospitals are actually contributing to the very problem they are trying to solve, and their negative effects are proportional to their age.

Taking into consideration the EU healthcare building stock, an average of 60% of the structures date back to before 1980 (a percentage ranging from 76% in Hungary to 74% in Sweden, 66% in Germany, 53% in Poland, and 30% in Spain), while only about 15% were built after 200 (Schimschar et al., 2011). As regards the Italian context, 4% of the operative hospitals were built before 1950, with 4 of them even dating back between 1846 and 1888. Today, the majority of the healthcare building stock (66%) is characterised by structures opened between 1950 and 2000, outdated both from the architectural and operational point of view, while only the 30% of the structures were built in the last twenty years (Ministero della Salute, 2018).

High hospital energy consumption is mostly due to extremely high demand for space heating and cooling throughout the year, caused by the need of high ventilation rates (English & Koeingshofer, 2015) and the strict requirements for microclimatic control (Buonomano et al., 2014; Čongradac et al. 2012; Singer & Tschudi, 2009), which result in a fast-growing need of electricity (Christiansen et al., 2016; Christiansen et al., 2015; Morgenstern et al., 2016; Rohde & Martinez, 2015; Salata et al. 2016), as already mentioned before (Figure 1.4).

Nevertheless, fossil fuels still represent the most widely used energy source, covering about 64% of end uses energy demand, primarily represented by heating, which accounts for 43%. As illustrated in Figure 1.5, fossil fuel use also provides process steam for humidification and sterilisation, which falls under "other" category, accounting for 10% of hospital energy consumption, followed by kitchen-related end uses and domestic hot water (DHW), which are responsible for 8% and 2% of energy consumption respectively.

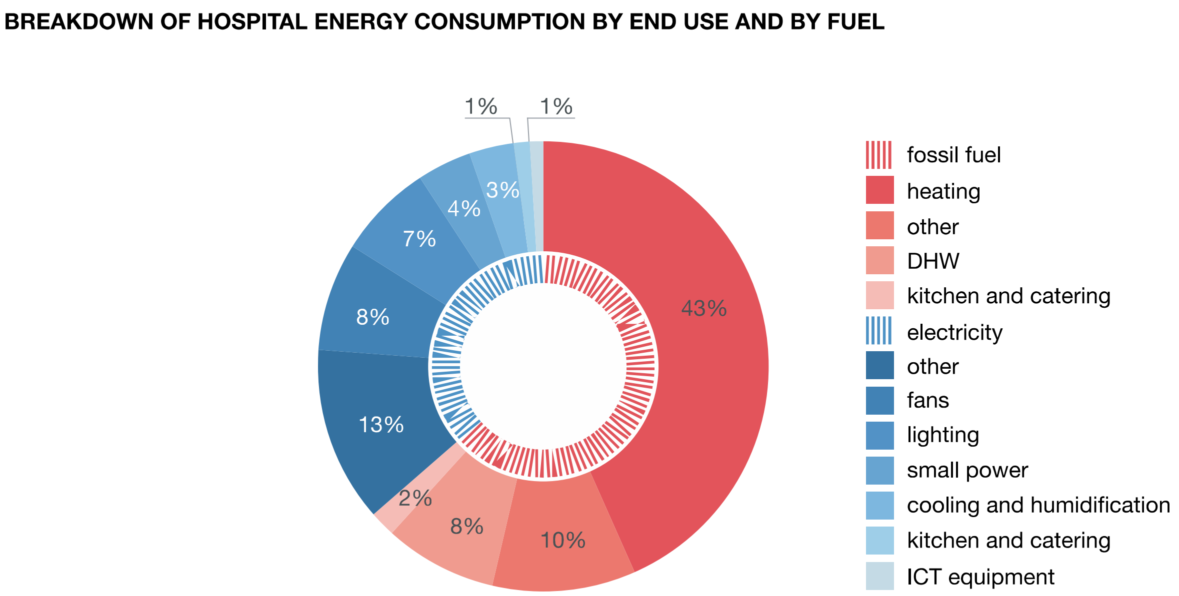


Figure 1.5. Share of hospital energy consumption by end use and by fuel type. Based on GOV.UK (2018a), GOV.UK (2016) and University of Washington IDL (2012) data. All rights reserved; as modified by the author.

Electricity is used for pumps, elevators and miscellaneous equipment, included in “other” category, accounting for 13% of hospital energy use. Much of pumps-related energy is connected to the movement of fluids, including those used in the cooling system of the hospital. Fans-related energy, representing 8% of total energy use, is largely driven by air handlers and the need to deliver sufficient air to meet code air change rates. Lighting is a dynamic consumption area. Nevertheless, as LED lighting and lighting control strategies are not commonly used in most of existing healthcare facilities, lighting is usually responsible for 7% of hospital energy consumption. Cooling and humidification represent about 3% of energy use, followed by kitchen-related end uses and ICT equipment (including medical and imaging equipment), both of them accounting for 1% of energy consumption (GOV.UK, 2018a; GOV.UK, 2016; University of Washington IDL, 2012).

The analysis of hospital energy consumption by end use allows to identify and develop specific energy saving strategies focused on larger energy users, rather than devoting time and effort to areas that would result in very small relative gains. For this reason, despite data available in literature illustrated above allow to have a robust and reliable energy framework, when considering a healthcare facility the analysis of hospital energy consumption by end use should be conducted for the specific case examined, in order to adopt energy saving measures as effective as possible.

1.2 Identifying reliable values for benchmarking

In the absence of a standard or benchmark it is difficult to compare energy consumption between different hospital buildings. Simply measuring the amount of energy used per a chosen time period does not take into account building size, configuration or type of use.

Against this background, energy use intensity (EUI), which expresses energy consumption per unit floor area, is a meaningful energy consumption indicator.

In the following tables values of total EUI (Table 1.2), EUI by energy source (Table 1.3) and EUI by end uses (Table 1.4) available in literature are reported, in order to provide a robust and reliable overview of hospital specific energy usage.

However, measurement and comparison of EUI among hospitals around the world is challenging and complex. While U.S. hospitals typically report metered energy usage including plug load, European and Asian hospitals do not, instead reporting the EUI of the building and building systems only. This makes direct comparison of hospital EUI globally difficult (Guenther & Vittori, 2013). For this reason, only studies focused on European healthcare facilities were reviewed and reported in the following lines.

Table 1.2. Overview of total EUI, reference values in literature

Source	Category	EUI ($kWh \cdot m^{-2}\, y^{-1}$)
BPIE, 2011	SI hospitals	270
	UK hospitals	405
	CZ hospitals	430
	FR hospitals	250
	FI hospitals	350
	BG hospitals	370
Choudhary, 2011	UK hospitals	
	median	480
	lower limit	194
	upper limit	1270
University of Washington IDL, 2012	Rikshospitalet (Norway)	438
	Akershus University Hospital (Norway)	369
	St. Olav's (Norway)	353
	Rigshospitalet (Denmark)	363
GOV.UK, 2016	UK hospitals	390
Papadopoulos, 2016	hospital in Oslo (Norway)	430
	hospital in Thessaloniki (Greece)	390

Table 1.3. Overview of EUI by energy source, reference values in literature

Source	Category	natural gas EUI ($kWh \cdot m^{-2}\, y^{-1}$)	electricity EUI ($kWh \cdot m^{-2}\, y^{-1}$)
BRECSU, 1996	UK acute hospital	510	108
DoH, 2006	UK General acute hospital	373	143
CIBSE, 2008	UK Hospital (Clinical and Research)	420	90
BBSR, 2009	DE Hospital with up to 250 beds	205	120
	DE Hospital with 251 to 1000 beds	250	115
	DE Hospital with more than 1000 beds	285	115
VDI, 2012	DE Hospital with up to 250 beds	289	53
	DE Hospital with 251 to 450 beds	243	67
	DE Hospital with 451 to 650 beds	314	77
	DE Hospital with 651 to 1000 beds	308	78
	DE Hospital with more than 1000 beds	446	164
GOV.UK, 2016	UK hospitals	260	120
NHS Digital, 2018	UK hospitals	268	96

Table 1.4. Overview of EUI by end use, reference values in literature

End use	natural gas EUI ($kWh \cdot m^{-2} y^{-1}$)	electricity EUI ($kWh \cdot m^{-2} y^{-1}$)
Heating	150	–
Hot water	50	–
Cooling & humidification	–	10
Fans	–	20
Lighting	–	30
Medical equipment	–	90
Other	44	6

source: GOV.UK, 2016

The analysis of the values outlined in Table 1.2 underlines that total EUI ranges from about 200 to 480 $kWh \cdot m^{-2}y^{-1}$, reaching an average of 360 $kWh \cdot m^{-2}y^{-1}$, if a peak value of 1270 $kWh \cdot m^{-2}y^{-1}$, decisively too higher than the other maximum values, is excluded. Taking into consideration EUI by energy source (Table 1.3), literary data report an average electricity EUI of nearly 100 $kWh \cdot m^{-2}y^{-1}$ and an average natural gas EUI of 320 $kWh \cdot m^{-2}y^{-1}$. Medical equipment is responsible for the highest electricity EUI, reaching 90 $kWh \cdot m^{-2}y^{-1}$, followed by lighting, fans and cooling, characterised by 30 $kWh \cdot m^{-2}y^{-1}$, 20 $kWh \cdot m^{-2}y^{-1}$ and 10 $kWh \cdot m^{-2}y^{-1}$ respectively. As regards natural gas EUI, this is primarily due to heating, which presents a value of 150 $kWh \cdot m^{-2}y^{-1}$, followed by hot water and "other", with 50 $kWh \cdot m^{-2}y^{-1}$ and 44 $kWh \cdot m^{-2}y^{-1}$ respectively (Table 1.4).

In order to aid a comprehensive interpretation of the data reviewed above, is necessary to underline that healthcare facilities have the highest EUI of non-residential buildings (Choudhary, 2011; Eckelman & Sherman, 2016; Papadopoulos, 2016; Ru & Shilin, 2019).

In addition, the steady changes in the procedures of care delivery, due to the fast-moving advances of the diagnostic techniques, require the continuous remodelling of the spaces in existing facilities, involving both architectural-distributive aspects and building plant systems. This process deeply impacts hospital energy consumption, underlining the need of forecasting these new dynamics also in terms of costs.

In 2016 the global health expenditure accounted for roughly 10% of the Gross Domestic Product (GDP), with the United States spending the most of any nation by far on its healthcare system (17.1%). Considering Italy, the country's national health service expenditures have increased of about 30% in the last twenty years, reaching 8.9 % of GDP (The World Bank, 2016). Among all healthcare expenditures, costs for energy consumption represent only a few percentage points within the economic balance sheet of a hospital. However, energy-related expenditures are responsible for a decisively significant value in absolute terms, which, if reduced, could make some financial resources available for other healthcare purposes, with important beneficial effects on the community.

Against this background, and in view of the increasingly stringent energy efficiency targets and environmental issues, the need of a more robust and reliable model to identify and manage the main end uses responsible for hospital energy consumption is becoming more and more important. Indeed, a similar model would allow to optimise the most energy intensive activities for a more effective usage of resources, also considering that a growing number of studies have uncovered a mismatch between the predicted energy performance of buildings and their actual measured energy use and resulting utility bills, an issue addressed as 'the performance gap' (CarbonBuzz; Cheshire & Menezes, 2013; de Wilde, 2014; Menezes et al., 2012).

Nevertheless, the assessment of energy performance and retrofit potentials for hospital buildings is very arduous because of the substantial size, energy-intensity and heterogeneity (Ascione et al., 2016), together with the lack of energy data from a sufficiently large number of buildings for benchmarking (Morgenstern et al., 2016). In the following section, a state of the art review of the existing studies about the evaluation and prediction of hospital energy behaviour is reported.

1.3 Energy analysis methods

The current scientific literature about energy performance assessment and forecasting models for healthcare facilities includes a huge variety of approaches which largely differ in the method of analysis, the energy issues investigated, the type of building - existing or prototype/modeled - or hospital spaces to which the method is applied, as well as the scale at which the research work is conducted.

The main methods are briefly reviewed in (de Wilde, 2014). Here are presented the first-principle models, which span from stationary calculations, via semi-dynamic methods, to dynamic simulation; the machine learning approach, which requires training data provided by either measurements or first-principle models, and covers techniques such as regression analysis, artificial neural networks, support vector machines; measurements, which include metering the energy delivered at building or sub-systems level on the basis of different temporal resolution (from annual intervals to only a few minutes or even seconds) and allow to capture also energy-related data, such as indoor and outdoor conditions, occupancy, and control systems.

An analysis of the studies available in literature shows that the majority of the works are based only on dynamic thermal simulation models (Adamu et al. 2012; Ascione et al., 2016; ASHRAE, 2012; ASHRAE, 2009; Bonnema et al., 2013; Bonnema et al., 2010a; Bonnema et al., 2010b; Buonomano et al., 2016; Burpee & Loveland, 2010; Tsoutsos et al. 2010), albeit some recent approaches also employ measurement data in order to calibrate the model (Ahmadzadehtalatapeh & Yau, 2011; Ascione et al., 2013; Buonomano et al., 2014; Lomas & Giridharan, 2012; Pagliarini et al. 2012; Santo, 2014; Short et al., 2012). Indeed, since the late '70s, building simulation is a well-recognized method for the building energy performance assessment (Malkawi & Augenbroe, 2003). Furthermore, as this approach requires the use of energy simulation programs, nowadays its application is increasing wider and wider due to mature and diffuse ICT technologies. The method is used both to predict the indoor air temperature and humidity in time-dependent external weather conditions and to assess the influence of different buildings features on the building thermohygrometric behaviour and comfort (Kolokotsa et al., 2011). Nevertheless, simulation-based methods are characterised by several difficulties in properly modeling the building-HVAC system for large structures - such as hospitals - and by time consuming simulations. Large models can also limit the number of possible simulations, since even modest retrofit proposals could imply changes to many parameters (Buonomano et al., 2014).

Conversely, simplified steady-state models, often purposely developed, are based on empirical and/or experimental mathematical models. In particular, the adoption of simplified methodologies related to several control techniques able to assess the possibilities for increasing energy efficiency in hospitals were presented by Čongradac et al. (2014, 2012). Here, the tool, which was tested and calibrated at the new emergency hospital located in Novi Sad, Serbia, enables fast analyses by avoiding complex dynamic modeling. Finally, some approaches are based only on on-site measurements (Christiansen et al., 2015; Morgenstern et al., 2016; Rohde & Martinez, 2015).

Taking into consideration the energy aspects investigated, it arises that, although a comprehensive analysis of the energy behaviour of hospital buildings should consider all levers affecting energy performance, current scientific literature does not provide worthy studies that explored all the energy related aspects. Čongradac et al. (2012) focused on hospital heating and cooling energy consumption, while other works investigated only electricity (Bagnasco et al., 2015; Christiansen et al., 2016; Christiansen et al., 2015; Morgenstern et al., 2016; Rohde & Martinez, 2015; Zorita et al., 2016), heat consumption for DHW (Bujak, 2010), or comfort in healthcare environments (Balaras et al., 2007; Buonomano et al., 2016; Iddon et al., 2015; Lomas & Giridharan, 2012; Short et al., 2012). Differently, a wide variety of studies deeply explored the benefits and cost-effectiveness of energy retrofit measures and energy saving measures, making a comparative analysis between different strategies (Ascione et al., 2016; Ascione et al., 2013; Buonomano et al., 2014; Čongradac et al., 2014) or focusing on only one of them and exploring some variations of it (Adamu et al., 2012; Ahmadzadehtalatapeh & Yau, 2011; Cho et al., 2014; Gimelli & Muccillo, 2013; Pagliarini et al. 2012; Santo, 2014; Tsoutsos et al., 2010).

A more critical review of the hospital building type and spaces examined in literature shows that these methods were rarely applied to existing and operative hospital structures (Ascione et al., 2013; Čongradac et al., 2012; Čongradac et al., 2014; Pagliarini et al. 2012; Santo, 2014). Most of the studies were developed considering a reference building representative of the hospital building category. Nevertheless, each reference building was defined on the base of different criteria, like the standards reported by regulations (ASHRAE, 2012; ASHRAE, 2009; Bonnema et al., 2013; Bonnema et al., 2010a; Bonnema et al., 2010b; Burpee & Loveland, 2010), statistical data coming from a large number of hospitals (Ascione et al., 2016), hospital templates or reports and datasets providing typical hospital characteristics (ASHRAE, 2012; ASHRAE, 2009; Bonnema et al., 2013; Bonnema et al., 2010a; Bonnema et al., 2010b), or the parameters dictated by the method employed (Buonomano et al., 2016). Again, several studies took into consideration only single hospital spaces (like a department) (Adamu et al. 2012; Ahmadzadehtalatapeh & Yau, 2011; Christiansen et al., 2015; Lomas & Giridharan, 2012; Morgenstern et al., 2016; Rohde & Martinez, 2015; Short et al., 2012), or only some buildings representative of the healthcare complex (Buonomano et al., 2014; Tsoutsos et al., 2010), due to the difficulties in modeling, calibrating, predicting and interpreting results for all the hospital spaces.

In addition, the majority of the aforementioned approaches analysed the hospital (either existing or prototype) at building level or focused just on some healthcare spaces or departments. Only few works investigated the whole hospital at departmental level (Ascione et al., 2016; ASHRAE, 2012; ASHRAE, 2009; Bonnema et al., 2013; Bonnema et al., 2010a; Bonnema et al., 2010b; Burpee & Loveland, 2010; Čongradac et al., 2012; Čongradac et al., 2014). Nevertheless, these studies did not refer all the energy related aspects to this space distinction.

Against this background, the Advanced Energy Design Guides (AEDGs) for Large Hospitals (ASHRAE, 2012) and for Small Hospitals and Healthcare Facilities (ASHRAE, 2009) – a product of a collaboration between ASHRAE, AIA, IES, USGBC, and DOE – together with the related Technical Support Documents (TSDs) (Bonnema et al., 2013; Bonnema et al., 2010a; Bonnema et al., 2010b) and a study developed by the University of Washington's Integrated Design Lab (IDL) (Burpee & Loveland, 2010), represent more comprehensive works. These studies thoroughly investigated the energy behaviour of hospital buildings by considering all the energy related aspects at departmental level. The works employed the dynamic thermal simulation approach applied to baseline and low-energy reference buildings in different climate zones.

More in detail, the two AEDGs (ASHRAE, 2012; ASHRAE, 2009) analysed baseline and energy saving parameters regarding the building envelope, vertical fenestration, lighting (natural and electric), HVAC, service water heating (SWH) and plug and process loads (PPLs), then developing specific strategies and ESMs, and finally calculating the attained savings. The guides use the macro-level classification of hospital spaces – the same used in scientific literature and regulation (AGENAS, 2003; Enciclopedia medica italiana, 1983; Palumbo, 1993; Rossi Prodi & Stocchetti, 1990; Setola, 2013) – distinguishing between Inpatient Units (IPUs), Diagnostic and Treatment Facilities (D&T), and nonclinical spaces, and provide prescriptions regarding daylighting, space layout and lighting power densities (LPDs) in relation to these three macro-areas.

Conversely, the three TSDs (Bonnema et al., 2013; Bonnema et al., 2010a; Bonnema et al., 2010b), which integrate the AEDGs, include a more comprehensive analysis of the surface distribution of hospital prototype distinguishing by all the space types. To the space categories identified were referred baseline and energy saving values for ventilation, total airflow requirements, LPDs, PPLs and SWH loads. Moreover, the documents include parameters regarding the building envelope, vertical fenestration, infiltration, exterior lighting, elevators and plant systems, along with the ESMs and calculated savings.

Similarly to the TSDs, the work of the University of Washington's IDL (Burpee & Loveland, 2010), focused on achieving a 60% reduction in hospital energy use, is based on an accurate distinction of the spaces according to their use. However, to this distinction are not referred any of the specifications provided by the work and regarding the building envelope, vertical fenestration, external surface, natural ventilation, lighting, building and plant systems, electricity and natural gas consumption by end use, building peak load components, and the related energy and cost savings.

The lack of worthy studies on hospital energy behaviour at departmental level represents a critical knowledge gap in the literature. Indeed, hospitals are known to show a very large variety of area specific energy consumption (Choudhary, 2011). Different departments and space types have different morphological characteristics, plant systems, conditioning requirements, occupancy, area, equipment, etc. Therefore, it is different their energy consumption and - what is the most important - the possibility of savings (ASHRAE, 2012; Čongradac et al., 2012; Morgenstern et al., 2016). For this reason, the academic literature has pointed out that hospital energy benchmarks need to be resolved for as specific an area as possible (Lomas & Ji, 2009; Singer, 2009).

Summarising, the review of the existing studies presented above underlines a series of critical issues regarding hospital energy behaviour assessment and prediction. Firstly, the shortage of works primarily based on measurement data causes a lack of data measured and estimated energy consumptions for hospital buildings. This is particularly true in Mediterranean climates, while an attempt is observed for U.K. National Health Service estate, Germany and Norway, see Refs. (Christiansen et al., 2015; Morgenstern et al., 2016; Rohde & Martinez, 2015). Secondly, a lack of studies exploring hospital energy performance by carefully considering the huge domain of the affecting factors means that the outcomes available in literature are strictly dependent on the investigated loads pattern and cannot be extended to different buildings functions and to different locations [15, 61]. This aspect, together with the absence of studies examining large samples of whole existing operative structures, also hinders the construction of more robust and reliable energy benchmarking. Again, despite increasing research activity in the past decade, it arises that energy analyses are still rarely based on departmental level, thus hospital energy consumption by space type remains largely unexplained (Christiansen et al., 2016).

2 Methodology

2.1 Research objectives

The purpose of the work firstly consists in the development of a preliminary analysis of hospital energy consumption able to identify the drivers of energy costs and applicable to all hospitals of any industrialised country in relation to the complexity of healthcare delivery. Secondly, the work aims at the definition of a simplified data-driven numerical model – accessible to operators and manageable without particular difficulties – capable to provide more precise results on the composition and value of the dominant end uses in energy consumption costs in relation to the type of the spaces. Data regarding morphological aspects of the facility and the main characteristics and operating hours of the different substations are used to build the model.

The numerical model was then validated with measured energy consumption data of six hospitals taken as case studies.

The main aspect of the work is represented by the methodological framework, which has been based on the identification of the energy needs and consumption from micro (single space) to macro scale (macro-area). Indeed, the setup of the whole method of analysis is aimed at addressing the weaknesses of the studies available in literature and reviewed in section 1.3, which look at the healthcare structure as a single and unique element of consumption, without a separation between different space types, or which focus only on a single hospital space type. Thus, the model enables to forecast the energy consumptions related to the refurbishment or modification of existing hospitals, analysing the impact of architectural and functional features, as well as of energy goals.

Furthermore, the exclusive use of measurement data collected from existing and operative hospitals provides a robust and reliable dataset and avoids the inaccuracies that can come from thermal building simulation methods. The model developed takes into consideration all the factors affecting building energy behaviour, providing a comprehensive tool.

The objective of the work, omitting complex dynamic modeling, is also to develop a method as simple as possible, which enables fast obtaining of fairly reliable results, being primarily intended for engineers, architects, technical staff responsible for the maintenance of healthcare facilities and energy managers.

2.2 Limitations of the study

The numerical model developed in the work evaluates hourly, daily, monthly and annual thermal energy consumption of hospital buildings for the following end uses:

- heating and summer reheating (when the latter is not carried out by using heat recovery from the condensers of the chiller units);
- production of steam used for humidification and sterilisation;
- DHW.

Thermal energy consumption for meal preparation was not considered in the analysis as this service is generally provided by central catering facilities. Furthermore, electricity consumption for air conditioning, motive power and lighting was not analysed due to the lack of reliable and robust measured data.

2.3 Structure of the method of analysis

Six hospitals located in Northern Italy were taken as case studies and data regarding their different departments, medical functions, HVAC system, morphological features of the buildings and levels of insulation, air change rates, operating hours, etc. were analysed in order to build a simplified data-driven numerical model for the assessment and forecasting of annual thermal energy consumption - including the energy consumed for summer reheating, DHW and steam used for humidification and sterilisation. Healthcare facilities located in the same province have been chosen in order to avoid the climate variables between different regions. Four of the six hospitals analysed have less than 250 hospital beds, thus representing small and medium-sized healthcare facilities, while two of them have between about 400 to 650 hospital beds. Therefore, the latter are representative of structures with

hospital departments providing highly complex and advanced healthcare, which are usually more energy-intensive due to necessity to meet high plant performance.
The design of the new assessment model has been developed into five steps.

The **first phase** concerned the definition of the main parameters connected to hospital comfort and energy consumption, taking into account both compulsory/suggested goals and experimental data.

The **second phase** consisted in the collection of information about the six hospitals considered. Data have been gathered through the use of sensors, the analysis of primary sources and of building plants, in order to arrange a simplified model to calculate energy needs of each healthcare facility.

The **third phase** was focused on the study of the distributive and energy related aspects of the different healthcare functions. This part contains the analysis of each case study from micro to macro scale cited before. Specifically, each healthcare facility was considered floor by floor and the spaces were distinguished in relation to the single space (micro scale), the functional area (FA) (medium scale), and the macro-area (macro scale), as illustrated in Table 2.1 and Figure 2.1, according to the taxonomy of hospital spaces used in scientific literature and regulation (AGENAS, 2003; ASHRAE, 2009; ASHRAE, 2012; Enciclopedia medica italiana, 1983; Palumbo, 1993; Rossi Prodi & Stocchetti, 1990; Setola, 2013).

Table 2.1. Subdivision of hospital spaces

Macro-Area	Functional area	Single space
Inpatient Units (IPUs)	Inpatient units (IPUs)	Patient rooms
		Examination rooms
		Medical offices
		Administrative offices
		Toilets and dressing rooms
		Connective spaces
		Storage rooms
		Technical spaces and services for patients and visitors*
Diagnostic and Treatment (D&T)	Accident and Emergency (A&E)	A&E specific spaces (observation unit, triages, etc.)
		Diagnostic/examination rooms
		Medical offices
		Administrative offices
		Toilets and dressing rooms
		Connective spaces
		Storage rooms
	Medical offices	Medical offices
		Toilets and dressing rooms
		Connective spaces
		Storage rooms
		Technical spaces and services for patients and visitors*
	Laboratories	Laboratories
		Medical offices
		Administrative offices
		Toilets and dressing rooms
		Connective spaces
		Storage rooms
		Technical spaces and services for patients and visitors*
	Operating theatres	Operating rooms (ORs) and support spaces
		Toilets and dressing rooms
		Connective spaces
		Storage rooms
		Technical spaces and services for patients and visitors*
	Outpatient department (OPD)	Consulting/examination/treatment rooms
		Medical offices
		Administrative offices
		Toilets and dressing rooms
		Connective spaces
		Storage rooms
		Technical spaces and services for patients and visitors*
	Diagnostic imaging	Diagnostic/examination rooms
		Medical offices
		Administrative offices
		Toilets and dressing rooms
		Connective spaces
		Storage rooms
		Technical spaces and services for patients and visitors*

Macro-Area	Functional area	Single space
General services	Kitchens and canteens	Kitchen and canteen specific spaces
		Toilets and dressing rooms
		Connective spaces
		Storage rooms
	Mortuary	Mortuary and support spaces
		Toilets and dressing rooms
		Connective spaces
		Storage rooms
	Administrative offices	Offices
		Toilets
		Connective spaces
		Storage rooms
	Toilets and dressing rooms	Toilets and dressing rooms
	Connective spaces	Connective spaces
	Storage rooms	Storage rooms
	Technical spaces and services	Technical spaces and services for patients and visitors*

*include mechanical spaces, meeting rooms, cafeteria, lounges, pharmacy, rehabilitation gym and ancillary spaces, chapel, etc.

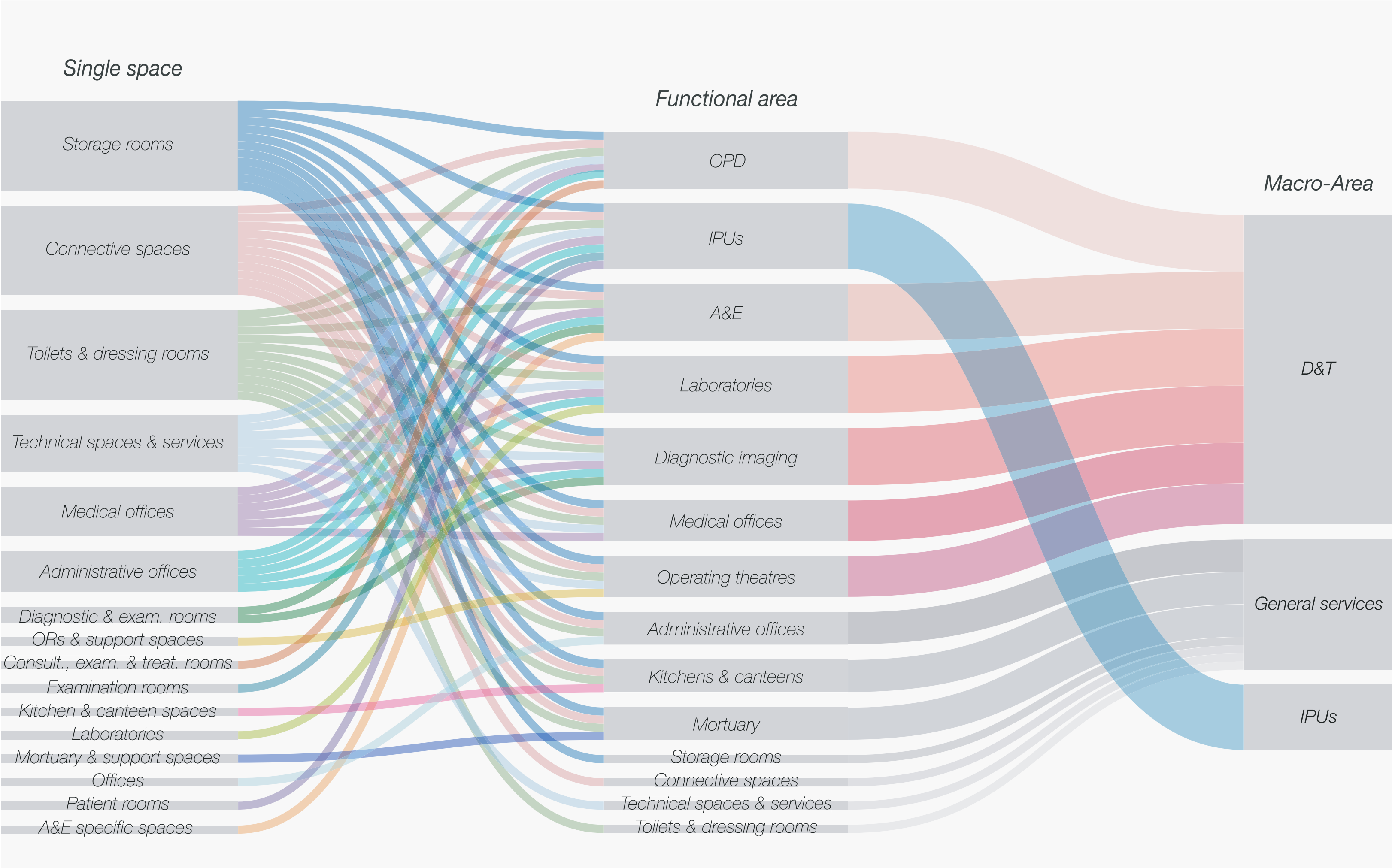


Figure 2.1. Subdivision of hospital spaces

The research results for each energy related aspect analysed have always been reported both at functional area level and at single space level, as outlined in Table 2.2 and in Table 2.3.

Table 2.2. Example of the presentation of the results obtained from the functional area level analysis, including specifications about some of the functional areas

Macro-Area	**Functional area**	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	IPUs*						
D&T	A&E*						
	OPD*						
	Diagnostic imaging*						
	Laboratories*						
	Medical offices*						
	Operating theatres*						
General services	Administrative offices*						
	Connective spaces						
	Kitchens and canteens*						
	Mortuary*						
	Storage rooms						
	Technical spaces and services						
	Toilets and dressing rooms						

* as outlined in Table 2.1, these are functional areas and include toilets, connective spaces, storage rooms, technical spaces and services, as well as the support spaces specific of each functional area

Table 2.3. Example of the presentation of the results obtained from the single space level analysis, including specifications about some of the spaces

Macro-Area	**Single space**	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	Patient rooms*						
D&T	A&E specific spaces*						
	Consulting/Examination rooms*						
	Diagnostic/Examination rooms*						
	Laboratories*						
	Medical offices*						
	ORs and support spaces*						
General services	Administrative offices*						
	Connective spaces						
	Kitchen and canteen specific spaces*						
	Mortuary and support spaces*						
	Storage rooms						
	Technical spaces and services						
	Toilets and dressing rooms						

*as outlined in Table 2.1, these are single spaces and do not include toilets, connective spaces, storage rooms, technical spaces and services, as well as other support spaces

The **fourth phase** was focused on the evaluation of actual annual thermal energy consumption for transmission, natural ventilation, mechanical ventilation, humidification, summer reheating, DHW and sterilisation (Figure 2.2). As air flow rates of the air handling units (AHUs) were related to the different functional areas, the assessment of actual energy consumption was conducted at functional area level. Heating, ventilation and humidification energy consumption was calculated on the base of hourly data of outdoor air temperature and relative humidity (RH) for winter 2009-2010 and 2010-2011, provided by Agenzia regionale per la protezione dell'ambiente (ARPA), as reported in Figure 2.3, which illustrates research methodology in detail. The aim was to achieve more robust and reliable energy consumption data compared to those obtained from theoretical energy demand. Indeed, this is assessed on the base of constant winter design climatic conditions, set to -5°C of air temperature and 80% of relative humidity for outdoor and, for the hospitals analysed, to 20°C of air temperature and 50% of relative humidity for indoor.

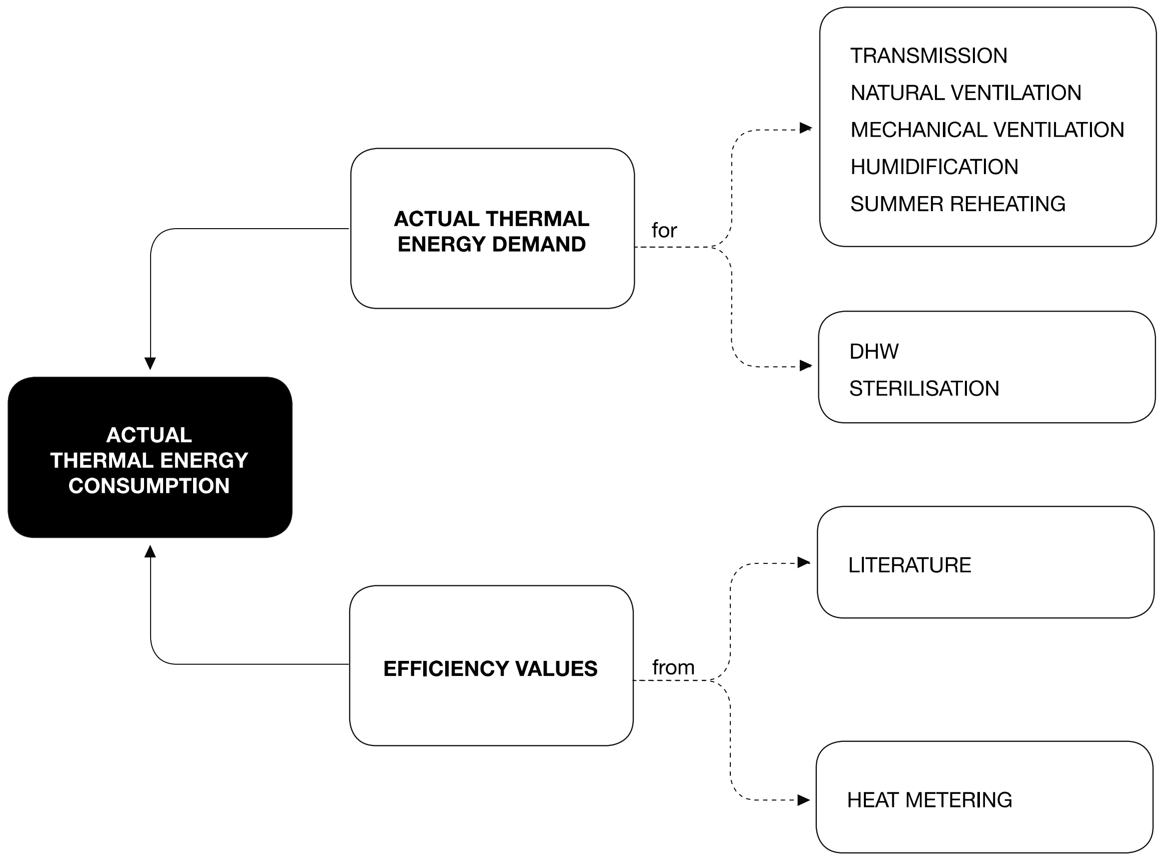


Figure 2.2. Summary of the research methodology

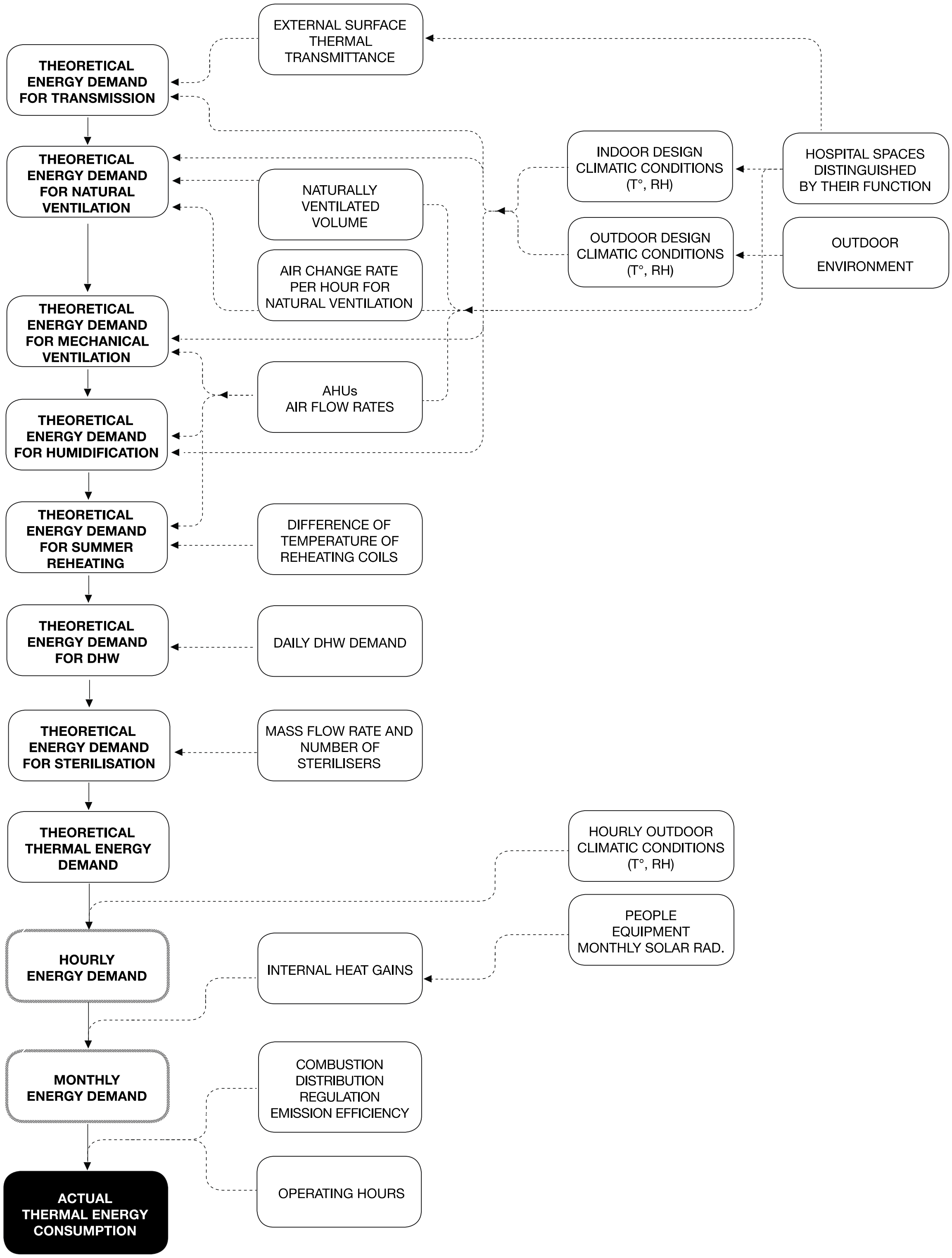


Figure 2.3. Research methodology

The **fifth phase** concerned the definition of the research parameters impacting on energy consumption and the development of the data-driven model for hospital energy assessment and forecasting. The elaboration and review of the results regarding energy usage obtained in the previous phase was aimed to conduct an in-depth analysis of the interface between the research parameters, highlighting the relation between them and the different use of spaces.

2.3.1 Case studies

The research analysed six hospitals taken as case studies (Figure 2.4, Tables 2.4 and 2.5) and identified as Hospital A, B, C, D, E and F. All the facilities are located in Northern Italy, and, more in detail, in the same province, in order to avoid the climate variables between different regions. With the aim of conducting a comprehensive study, and developing a robust and reliable model, hospitals with less than 250 hospital beds and hospitals with 400 to 650 hospital beds were selected. The former are representative of small and medium-sized facilities, while the latter are representative of structures with hospital departments providing highly complex and advanced healthcare, which are usually more energy-intensive due to necessity to meet high plant performance.

Figure 2.4. Planimetric diagrams of the hospitals analysed

Table 2.4. Main characteristics of the hospitals analysed

Hospital	Year of construction	Conditioned floor area (m²)	S/V*	S/Conditioned floor area
A	1900-1940	3,385	0.43	1.36
B	1940-1980	6,033	0.54	1.47
C	1940-1980	8,185	0.43	1.54
D	1900-1940	13,165	0.56	1.51
E	1900-1940	50,786	0.43	1.45
F	1940-1980	90,121	0.34	1.11

* S = external surface and V = conditioned volume

Table 2.5. Hospitals' departments and number of hospital beds

Departments	**A**	**B**	**C**	**D**	**E**	**F**
Anaesthetics			O	O	O	O
Breast care				O	O	O
Cardiology				O	O	O
Care of the elderly				O		O
Dialysis			O			O
Ear nose and throat (ENT)					O	O
Endocrinology				O	O	O
Extensive Rehabilitation					O	
Accident and Emergency	O	O	O	O		O
Functional Rehabilitation		O				
Gastroenterology				O	O	O
General surgery	O	O	O	O	O	O
Gynaecology		O	O			O
Internal Medicine	O	O	O	O	O	O
Long-term care		O	O	O	O	O
Maternity and Gynaecology				O		O
Medical laboratory				O	O	O
Neurology					O	O
Oncology			O	O	O	
Ophthalmology				O		O
Orthopaedics				O		O
Pediatrics				O		O
Radiology	O	O	O	O	O	O
Rehabilitation Medicine			O	O	O	O
Specialized Surgery				O	O	O
Urology						O
Hospital beds	89	92	114	221	372	652

2.4 Research outputs and impact

The main output of the work is a simplified numerical model, implemented in Microsoft Excel, which allows to assess annual thermal energy consumption - including the energy consumed for summer reheating, DHW and steam used for humidification and sterilisation - of a hospital when the following data are known:

- morphological and architectural features of the spaces;
- characteristics of the components of the building envelope;
- air change rates for each type of space;
- indoor design thermo-hygrometric conditions for each type of space and hours they are in use;

- outdoor hourly thermo-hygrometric conditions and average monthly solar radiation (direct and diffuse), usually available in the databases of Regional Environmental Protection Agencies;
- water consumption for DHW production;
- types, characteristics and operating hours of sterilisers (whether sterilisation is done by steam using centralised production or through local electrical systems);
- the presence of heat recovery systems in the AHUs.

Secondly, the methodological framework based on the identification of the energy needs and consumptions from micro (single space) to macro scale (macro-area) allows to have energy consumption per unit conditioned floor area and volume in relation to the type of hospital spaces.

Thus, the model developed within the work enables to continuously check and optimise hospital energy consumption in relation to the operating hours of the different substations. At the same time, it allows to forecast changes in energy consumption related to the refurbishment or modification of the spaces in existing hospitals, analysing the impact of architectural and functional features. For this reason, the model is considered of particular interest to hospital managers, as the steady changes in the procedures of care delivery, due to the fast-moving advances of the diagnostic techniques, require the continuous remodelling of the spaces in healthcare facilities, often involving both architectural-distributive aspects and an increase in the power of thermoelectric power plants.

2.5 Stakeholders of the research

The different types of contributions - analytical, methodological and empirical - that are expected to emerge from the research project will benefit a large number of stakeholders.

Public organisations and institutions (mainly related to the hospital field) will be assisted by robust and reliable data in defining and implementing effective energy saving measures in energy policies and strategies both at national and international level.

Private organisations holding and managing big real estates will be enabled to cut energy-related costs and invest the saved resources to improve healthcare spaces and services.

Universities and research community may further develop the results obtained in this work and define composite benchmarks for hospitals by taking into account differing energy intensities at a departmental level. Furthermore, being based on larger sample sizes, the work will increase the reliability of the established consumption figures.

Energy managers will benefit a robust set of assessment criteria to evaluate the energy saving potential (and paving the base to new hospital standards), this analysing the impact of architectural and functional features together with thermal and energy goals

The analysis of hospital energy consumption by end use allows to identify and develop specific energy saving strategies focused on larger energy users, rather than devoting time and effort to areas that would result in very small relative gains

Architects and engineers will be provided with a simple energy analysis and forecasting tool that will support them when planning a refurbishment or a layout modification within healthcare facilities. Furthermore, professionals interested in further low carbon hospital design could be assisted in exploring how different physical and logistical arrangements can enable low carbon health care.

3 Analysis of the healthcare functions

Similarly to the investigation methodology used by Čongradac et al. (Čongradac et al., 2012), the entire hospital buildings were created in Excel and defined room by room, to which were referred the measurement data collected. After providing a series of input data (general building data, building envelope data, internal heat loads, design climatic conditions, room location, orientation and function), a number of intermediate results were calculated, always referred to the type of spaces, like the conditioned floor area and external surface.

As reported in Tables 3.1-3.2 and in Figures 3.1-3.2, the research findings regarding the percentage distribution of the conditioned floor area for the six hospitals were compared to the values reported in Refs. (Bonnema et al., 2013; Bonnema et al., 2010a; Bonnema et al., 2010b; Burpee & Loveland, 2010). Although the studies exposed in the Refs. used building simulation methods and were based on prototype buildings and not real case studies, they were selected for the comparison since they are the only ones which analysed the hospital building by making a clear and comprehensive distinction of the spaces in relation to their use. In order to aid a proper interpretation of the first results, it is necessary to underline that the TSD for Small Hospitals and Healthcare Facilities (Bonnema et al., 2010a) refers to structures with a surface up to about 8.000 m^2, such as hospitals A, B and C, while the TSD for Large Hospital (Bonnema et al., 2013; Bonnema et al., 2010b) regards structures with a surface ranging from about 9.000 to 46.000 m^2, a category to which hospitals D, E and F belongs. The study developed by the University of Washington's IDL (Burpee & Loveland, 2010) analyses two types of hospital building form: a traditional and compact form, like hospitals A, C, E and F whose S/V ratio ranges from 0,34 to 0,43, and a more articulated one, like hospitals B and D, having a S/V ratio between 0,54 and 0,56 (see Table 2.4). In addition, both the TSDs analysed the hospital spaces at single space level, while the work of the IDL distinguished the spaces at department level. For this reason, the analysis of the six hospitals at single space level is compared to the results of the TSDs, while the analysis of the hospitals at functional area level is compared to the values reported by the IDL.

All the results outlined in this section, here expressed as a percentage, are additionally expressed in absolute terms in Appendix A.

Table 3.1. Distribution of the conditioned floor area in relation to the use of the spaces in hospitals with a compact form and in those with an articulated form

	Conditioned floor area (%)							
	Hospitals with a compact form					Hospitals with an articulated form		
Functional area	**A**	**C**	**E**	**F**	**IDL**	**B**	**D**	**IDL**
IPUs	31	27	35	33	32	26	34	42
A&E	3	8	0	1	4	2	3	4
Medical offices	4	5	4	3	11	5	5	10
Administrative offices	3	6	3	4	0	6	4	0
Laboratories	2	3	4	4	3	7	5	3
Operating theatres	10	4	6	8	9	5	4	9
OPD	14	6	9	8	0	11	18	0
Diagnostic imaging	4	4	9	4	6	4	3	6
Kitchens and canteens	6	3	2	4	2	4	4	2
Mortuary	0	1	1	1	0	1	0	0
Toilets and dressing rooms	4	5	4	3	0	2	4	0
Connective spaces	14	20	15	22	20	16	13	11
Storage rooms	1	3	3	1	3	4	0	3
Technical spaces and services	4	5	5	3	9	6	3	9
Macro-Area								
IPUs	31	27	35	33	32	26	34	42
D&T	37	30	32	29	23	35	38	22
General services	32	43	33	38	45	39	28	36

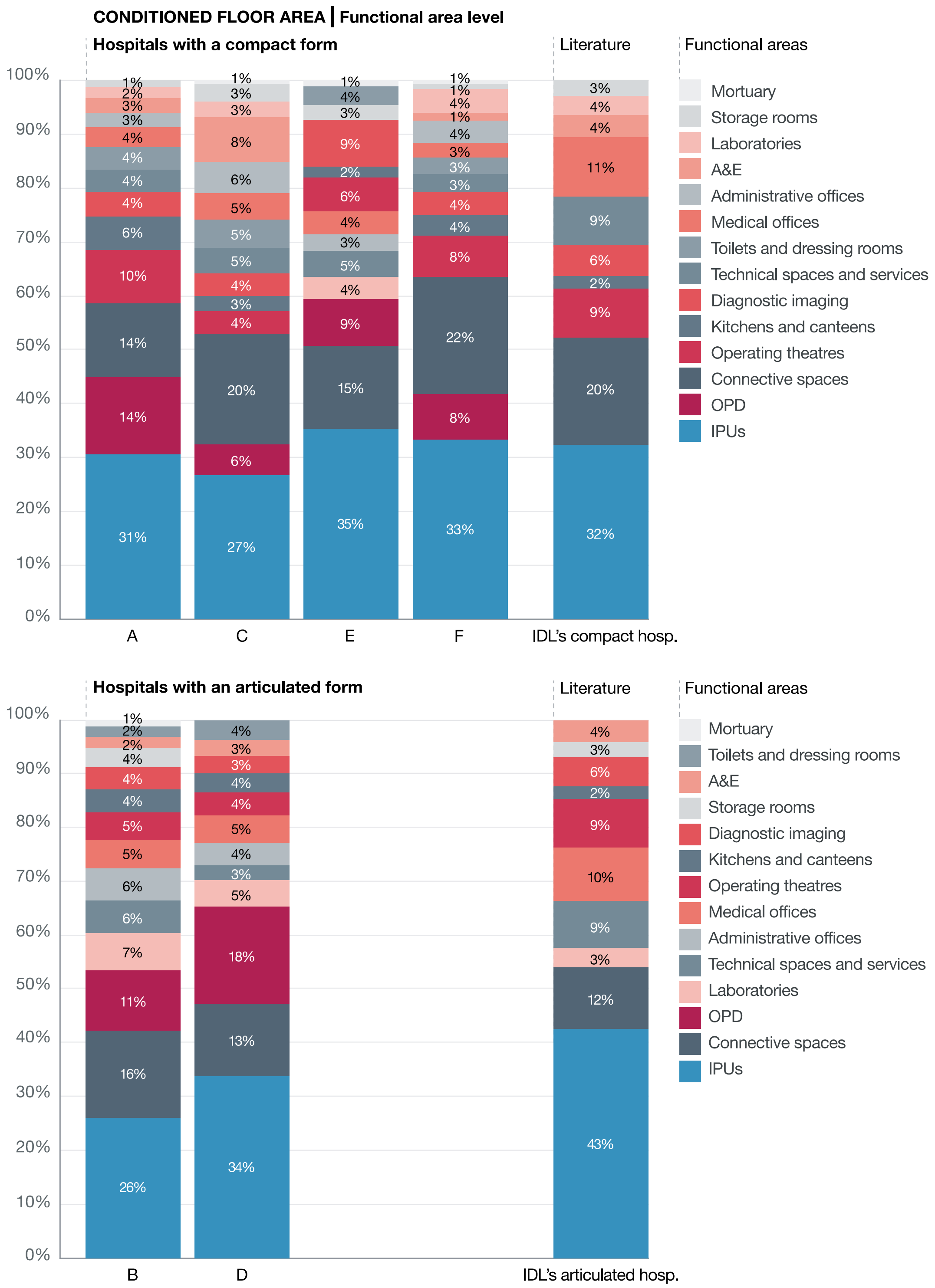


Figure 3.1. Distribution of the conditioned floor area by functional area in hospitals with a compact form and in those with an articulated form

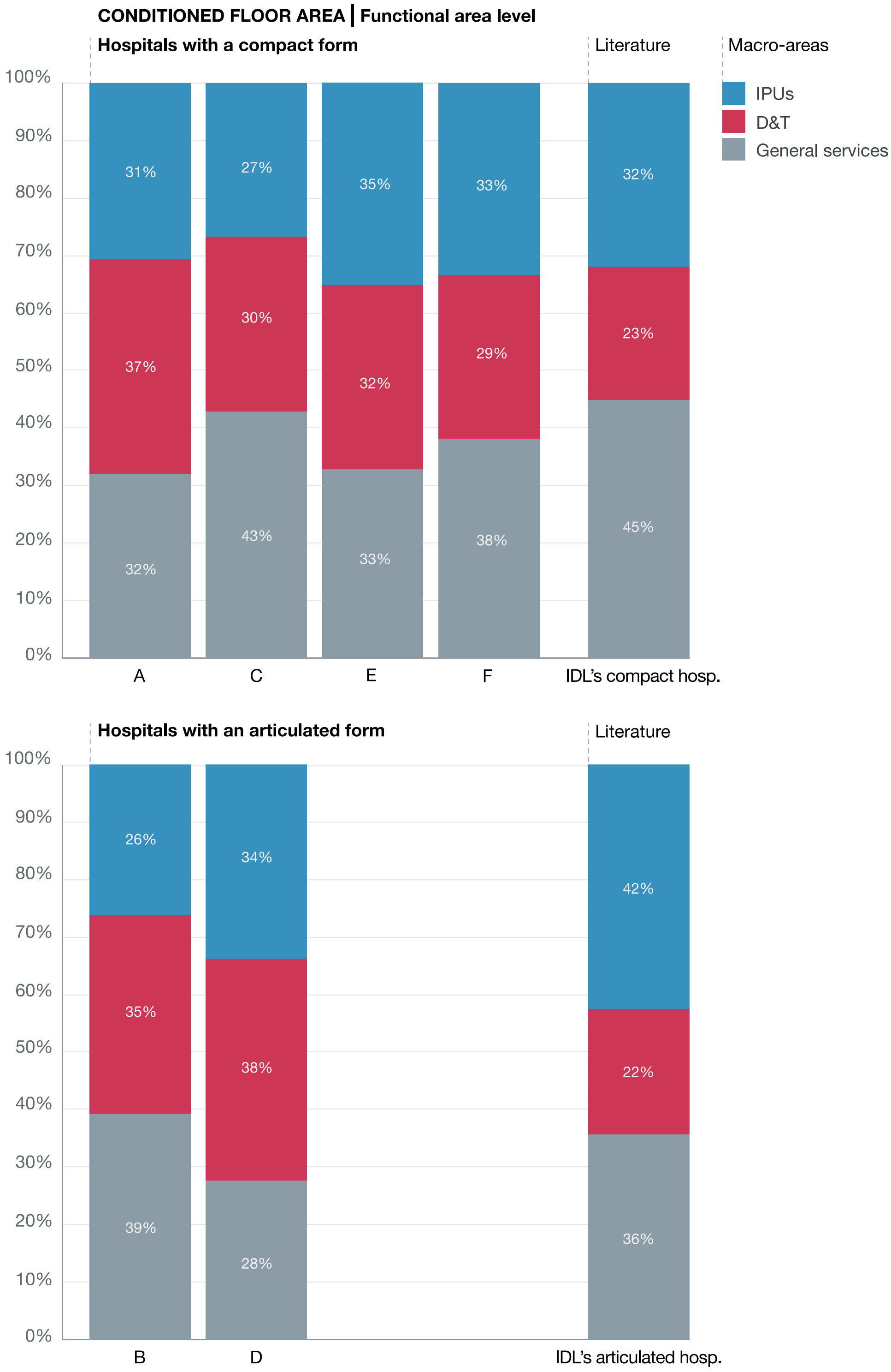


Figure 3.2. Distribution of the conditioned floor area by macro-area on the base of functional area level distinction

Table 3.2. Distribution of the conditioned floor area in relation to the use of the spaces in small and large hospitals

	Conditioned floor area (%)							
	Small hospitals				Large hospitals			
Single space	**A**	**B**	**C**	**TSD***	**D**	**E**	**F**	**TSD****
Patient rooms	17	14	15	10	16	10	12	24
A&E specific spaces	2	1	0	1	1	0	0	2
Medical offices	5	7	6	22	6	8	7	21
Administrative offices	6	7	6	0	7	5	5	0
Laboratories	2	5	3	2	4	3	3	3
ORs and support spaces	7	3	2	7	2	3	3	8
Consulting/Examination rooms	8	9	9	6	12	6	6	5
Diagnostic/Examination rooms	2	2	2	2	1	3	2	3
Kitchen and canteen specific spaces	4	4	3	3	2	2	3	2
Mortuary and support spaces	0	1	1	0	0	0	0	0
Toilets and dressing rooms	9	9	10	5	9	10	9	1
Connective spaces	29	29	32	23	34	36	40	16
Storage rooms	5	3	5	9	1	7	5	10
Technical spaces and services	5	6	5	11	5	7	5	6
Macro-Area								
IPUs	17	14	15	10	15	10	12	24
D&T	26	27	22	17	27	23	20	20
General services	57	59	63	73	58	67	68	56

* Bonnema et al. (2010a)

** Bonnema et al. (2010b)

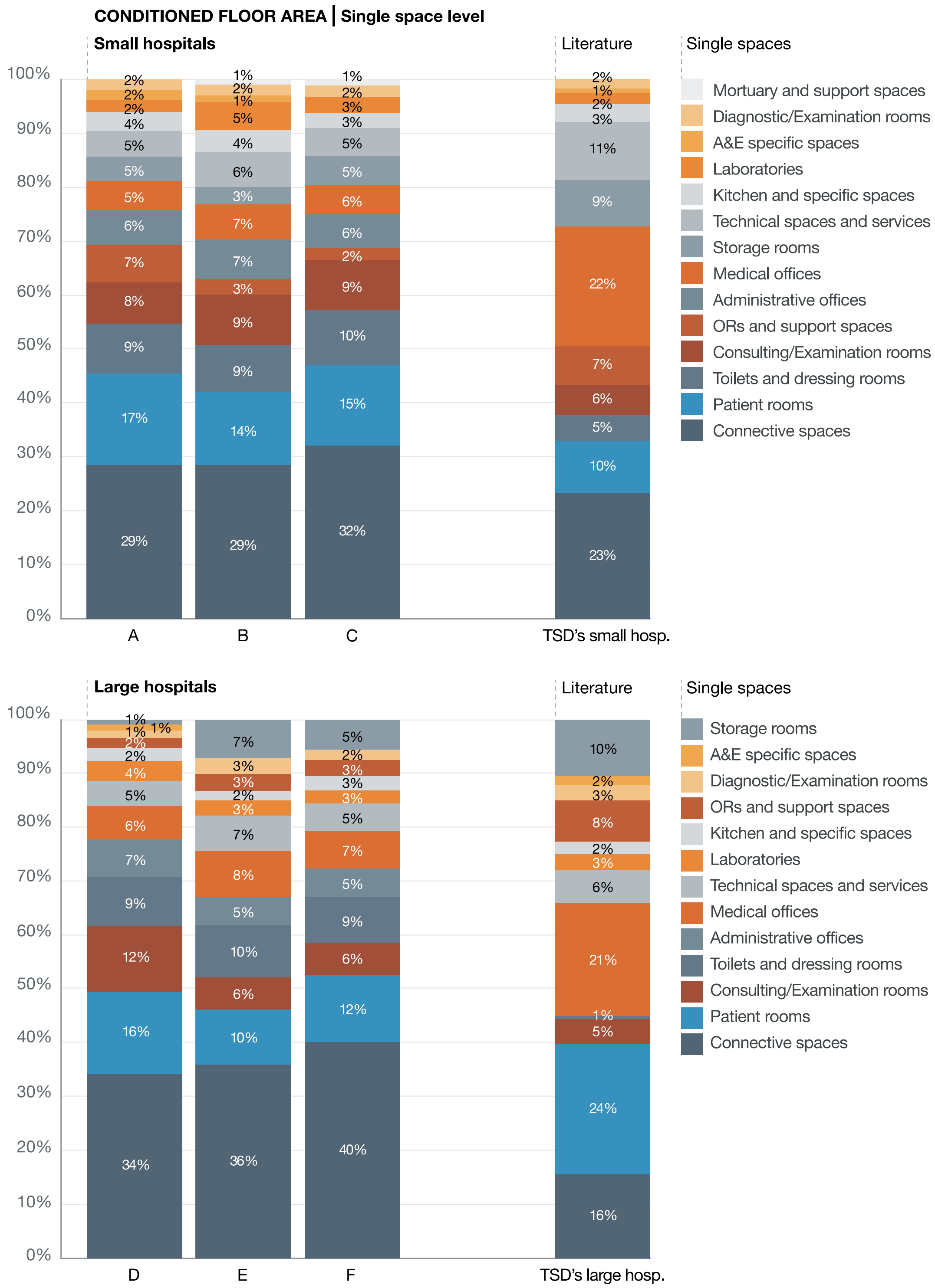


Figure 3.3. Distribution of the conditioned floor area by single space in hospitals with a compact form and in those with an articulated form

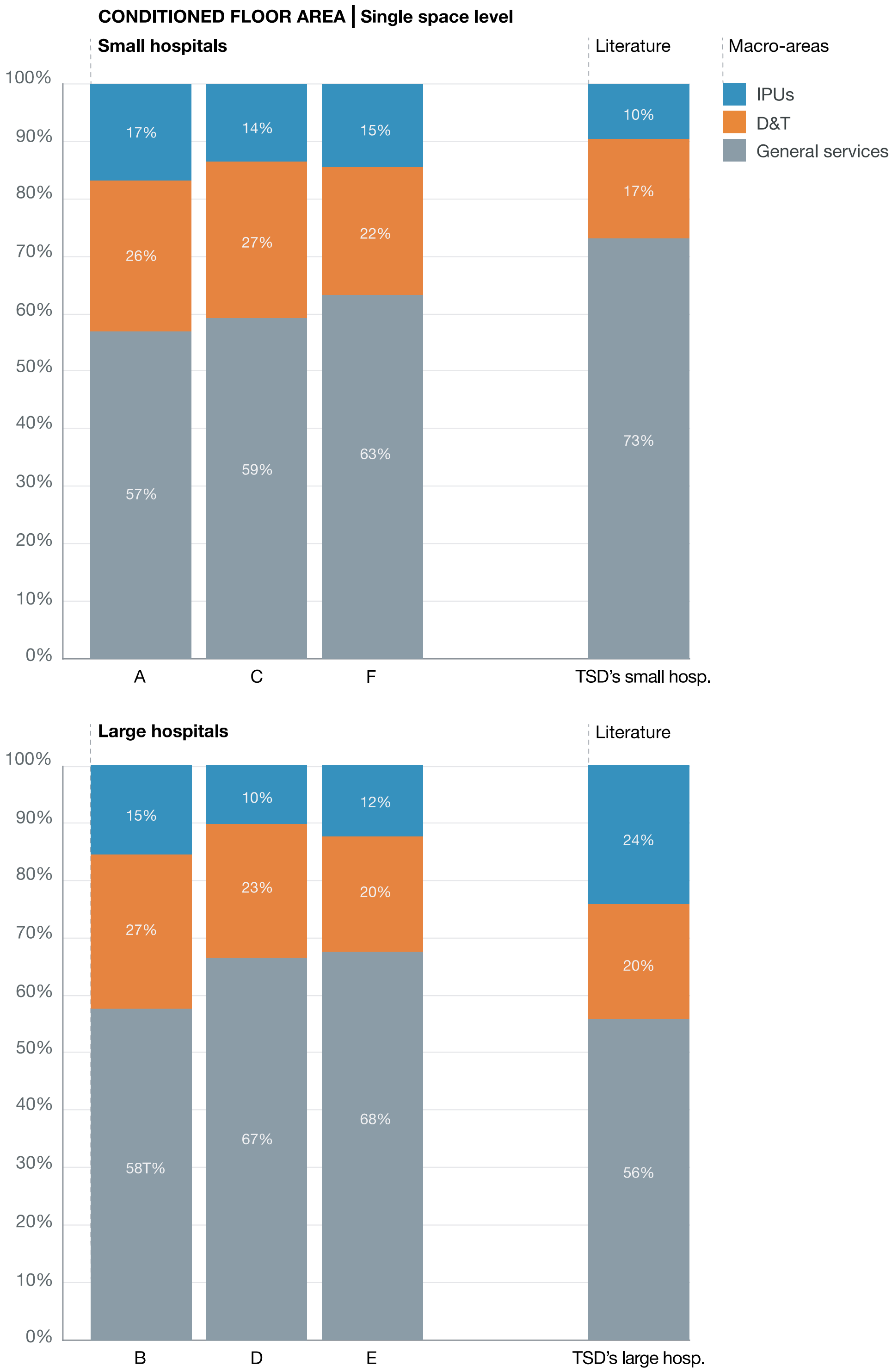


Figure 3.4. Distribution of the conditioned floor area by macro-area on the base of single space level distinction

Despite healthcare is characterised by the steady shift from inpatient toward outpatient care, the data exposed above show that IPUs at functional area level and patient rooms at single space level are the first and the second space type, respectively, to have an extremely high impact on the distribution of the conditioned floor area, followed and preceded by connective spaces (Tables 3.1-3.2 and Figures 3.1-3.3).

However, for a proper interpretation of the data is necessary to underline that half of the hospitals analysed date back to before 1940, while the others were built before 1980 (Tables 2.4). Therefore, considered the difficulties in space flexibility and layout reorganisation typical of outdated structures, the decrease of patient rooms is less visible in the case studies examined. This process is more evident in the analysis of the conditioned floor area at macro-area level, which underlines that general services are the most impacting space category (Tables 3.1-3.2 and Figures 3.2-3.4).

Besides IPUs and patient rooms, operating theatres and outpatient department (OPD), at functional area level, and consulting and examination rooms, at single space level, have a quite important role in the distribution of the hospital conditioned floor area, due to the advances in medical procedures and the trend from inpatient toward ambulatory care (Tables 3.1-3.2 and Figures 3.1-3.3).

The values regarding the distribution of the external surface in the hospital analysed were compared to the work of the IDL (Burpee & Loveland, 2010), as outlined in Table 3.3 and Figure 3.5, since this is the only one that distinguishes between transparent and opaque building envelope components.

Albeit none of the works reviewed above explored the external surface distribution by space type, for the sake of completeness in the following tables are reported the findings regarding the six hospitals analysed. Besides total external surface (from Table 3.4 to 3.7 and from Figure 3.6 to 3.9) the external surface of external walls (from Table 3.8 to 3.11 and from Figure 3.10 to 3.13) and of windows were analysed (from Table 3.12 to 3.15 and from Figure 3.14 to 3.17). The average of the values obtained for hospitals A, B, C and D were assumed to be representative of the external surface distribution in small hospitals, while for large facilities it was considered the trend observed for hospital E and F.

Table 3.3. Distribution of the external surface in relation to the building envelope components in hospitals with a compact form and in hospitals with an articulated one

	External surface (%)							
	Hosp. with a compact form				Hosp. with an articulated form			
Building envelope component	**A**	**C**	**F**	**IDL***	**B**	**D**	**E**	**IDL***
N windows	25	17	24	31	0	25	25	19
NE windows	0	0	8	0	25	0	3	0
NW windows	0	6	10	0	32	0	7	0
E windows	18	31	7	22	0	28	14	28
S windows	30	15	26	29	0	25	26	25
SE windows	0	3	10	0	28	0	6	0
SW windows	0	1	7	9	11	0	3	0
W windows	28	26	7	9	0	21	14	29
Skylights	0	0	0	0	2	0	0	0
Overall Windows	10	10	11	12	8	8	10	15
Opaque components	90	90	89	88	92	92	90	85

* Burpee & Loveland (2010)

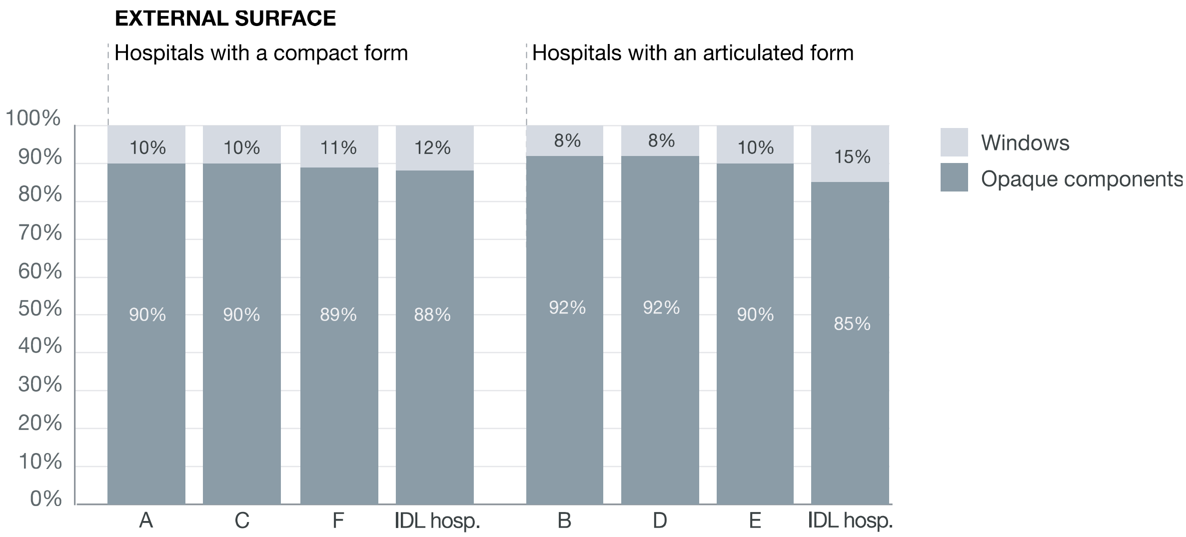


Figure 3.5. Distribution of external surface in relation to building envelope components

Table 3.4. Distribution of external surface at functional area level

	External surface (%)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	22	15	22	25	32	22
A&E	4	4	4	3	0	1
OPD	11	14	6	19	8	8
Diagnostic imaging	6	3	5	4	9	3
Laboratories	2	8	3	5	3	6
Medical offices	3	5	7	5	5	3
Operating theatres	13	6	4	3	5	7
Administrative offices	3	8	8	5	4	7
Connective spaces	14	15	20	19	16	23
Kitchens and canteens	10	6	4	5	3	7
Mortuary	0	2	1	0	0	0
Storage rooms	2	4	5	0	4	2
Technical spaces and services	4	8	5	3	6	4
Toilets and dressing rooms	6	3	6	5	5	6
Macro-Area						
IPUs	22	15	22	26	32	22
D&T	39	40	29	38	30	29
General services	39	45	49	36	38	49

Table 3.5. Distribution of external surface at functional area level in small and large hospitals

	External surface (%)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	21	27
A&E	4	1
OPD	13	8
Diagnostic imaging	4	6
Laboratories	4	5
Medical offices	5	4
Operating theatres	6	6
Administrative offices	6	6
Connective spaces	17	20
Kitchens and canteens	6	5
Mortuary	1	0
Storage rooms	3	3
Technical spaces and services	5	5
Toilets and dressing rooms	5	5
Macro-Area		
IPUs	21	27
D&T	37	29
General services	42	44

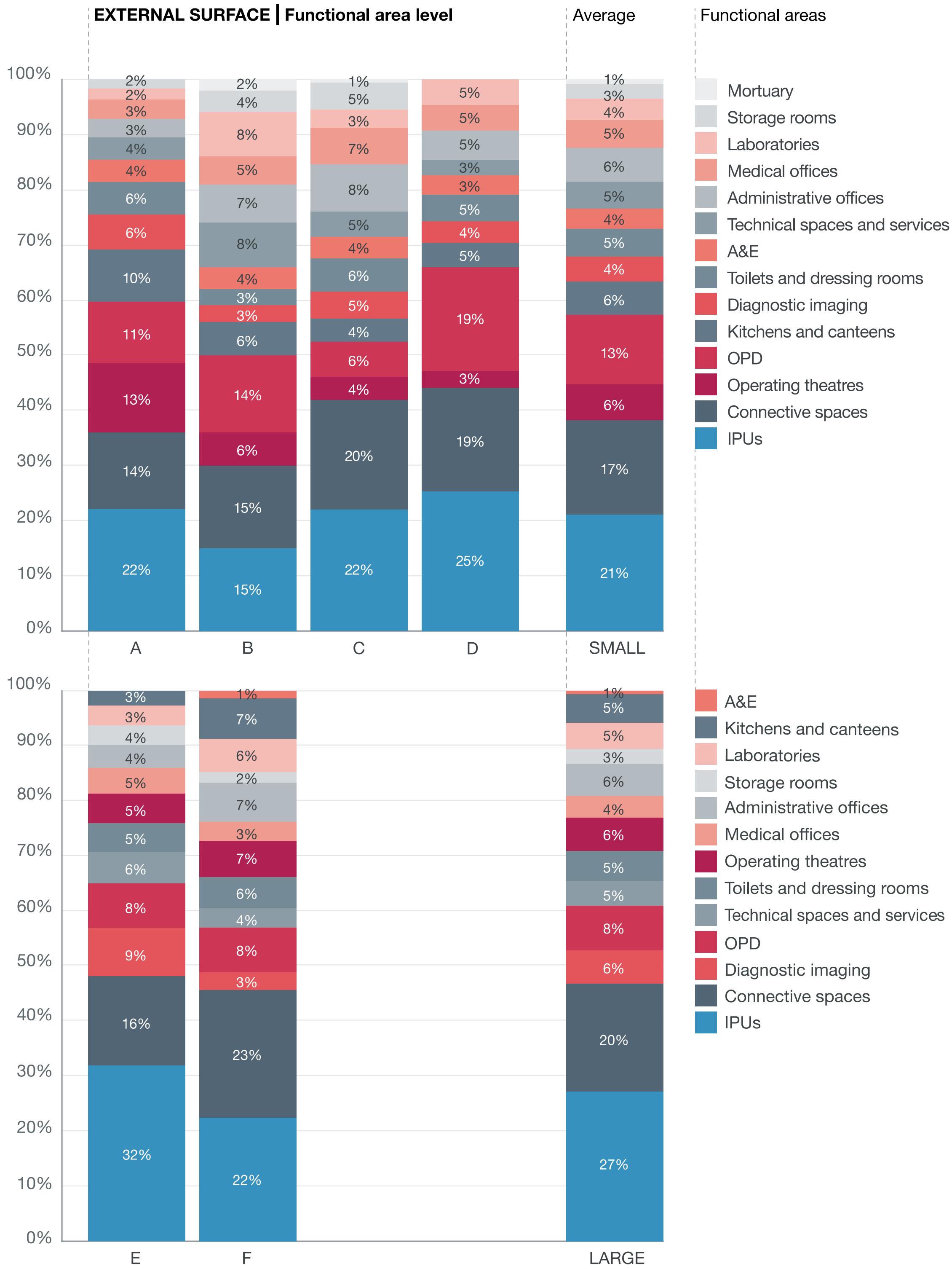


Figure 3.6. Distribution of external surface by functional area

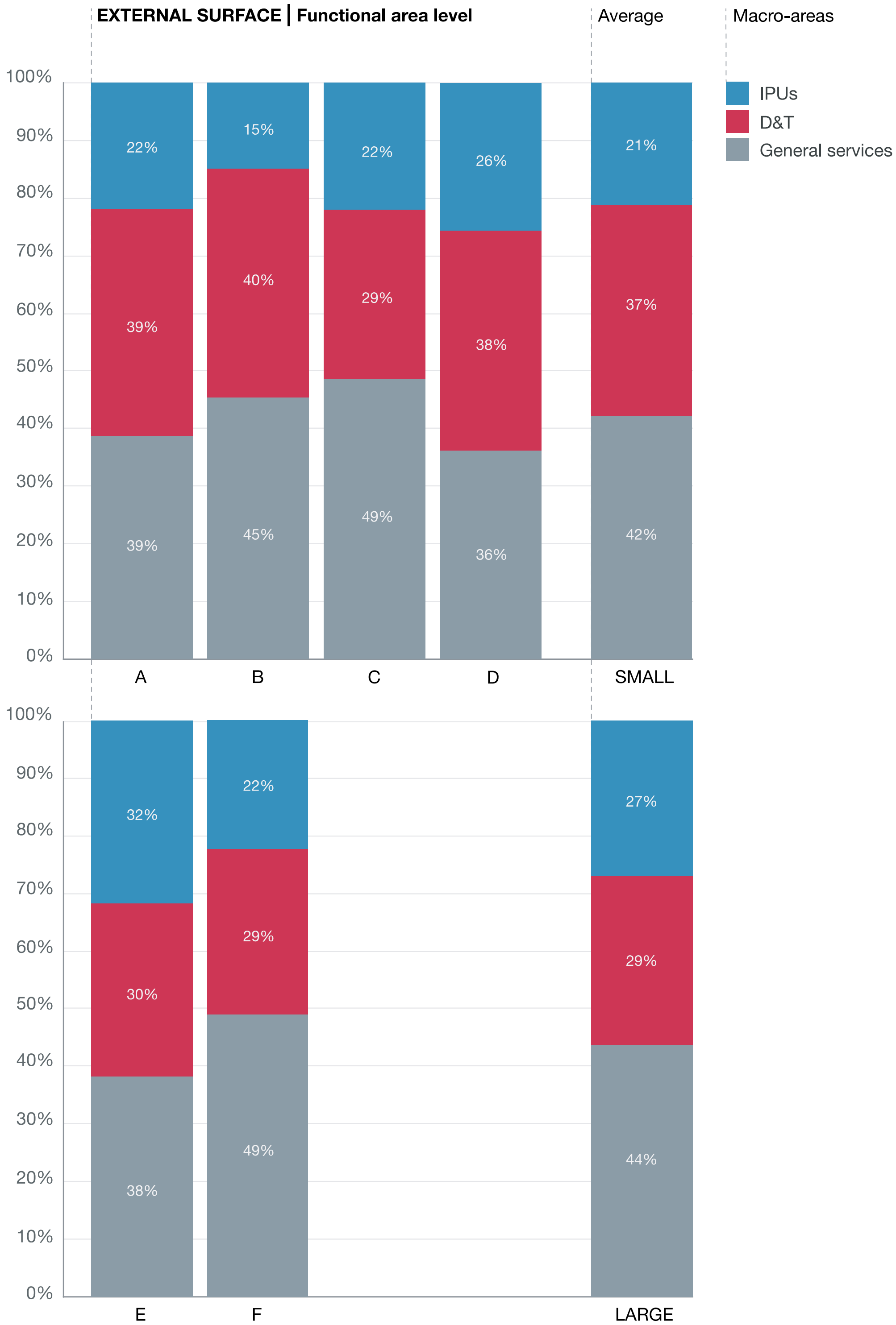


Figure 3.7. Distribution of external surface by macro-area on the base of functional area level distinction

Table 3.6. Distribution of external surface at single space level

	External surface (%)					
Single space	**A**	**B**	**C**	**D**	**E**	**F**
Patient rooms	13	8	15	12	10	8
A&E specific spaces	4	2	0	1	0	0
Consulting/Examination rooms	7	10	8	12	6	6
Diagnostic/Examination rooms	3	2	2	2	3	1
Laboratories	2	6	3	4	2	3
Medical offices	5	6	8	6	9	7
ORs and support spaces	8	3	2	1	3	2
Administrative offices	6	8	9	7	6	8
Connective spaces	25	25	25	38	32	36
Kitchen and canteen specific spaces	5	6	4	3	2	5
Mortuary and support spaces	0	1	1	0	0	0
Storage rooms	6	4	6	1	8	6
Technical spaces and services	4	8	5	4	7	5
Toilets and dressing rooms	11	12	12	10	10	11
Macro-Area						
IPUs	13	8	15	12	10	8
D&T	28	28	23	26	23	20
General services	58	64	62	63	67	72

Table 3.7. Distribution of external surface at single space level in small and large hospitals

	External surface (%)	
Single space	**Small Hospital**	**Large Hospital**
Patient rooms	12	9
A&E specific spaces	1	0
Consulting/Examination rooms	10	6
Diagnostic/Examination rooms	2	2
Laboratories	4	3
Medical offices	6	8
ORs and support spaces	2	3
Administrative offices	8	8
Connective spaces	30	34
Kitchen and canteen specific spaces	4	4
Mortuary and support spaces	1	0
Storage rooms	3	7
Technical spaces and services	5	6
Toilets and dressing rooms	11	11
Macro-Area		
IPUs	12	9
D&T	26	21
General services	63	70

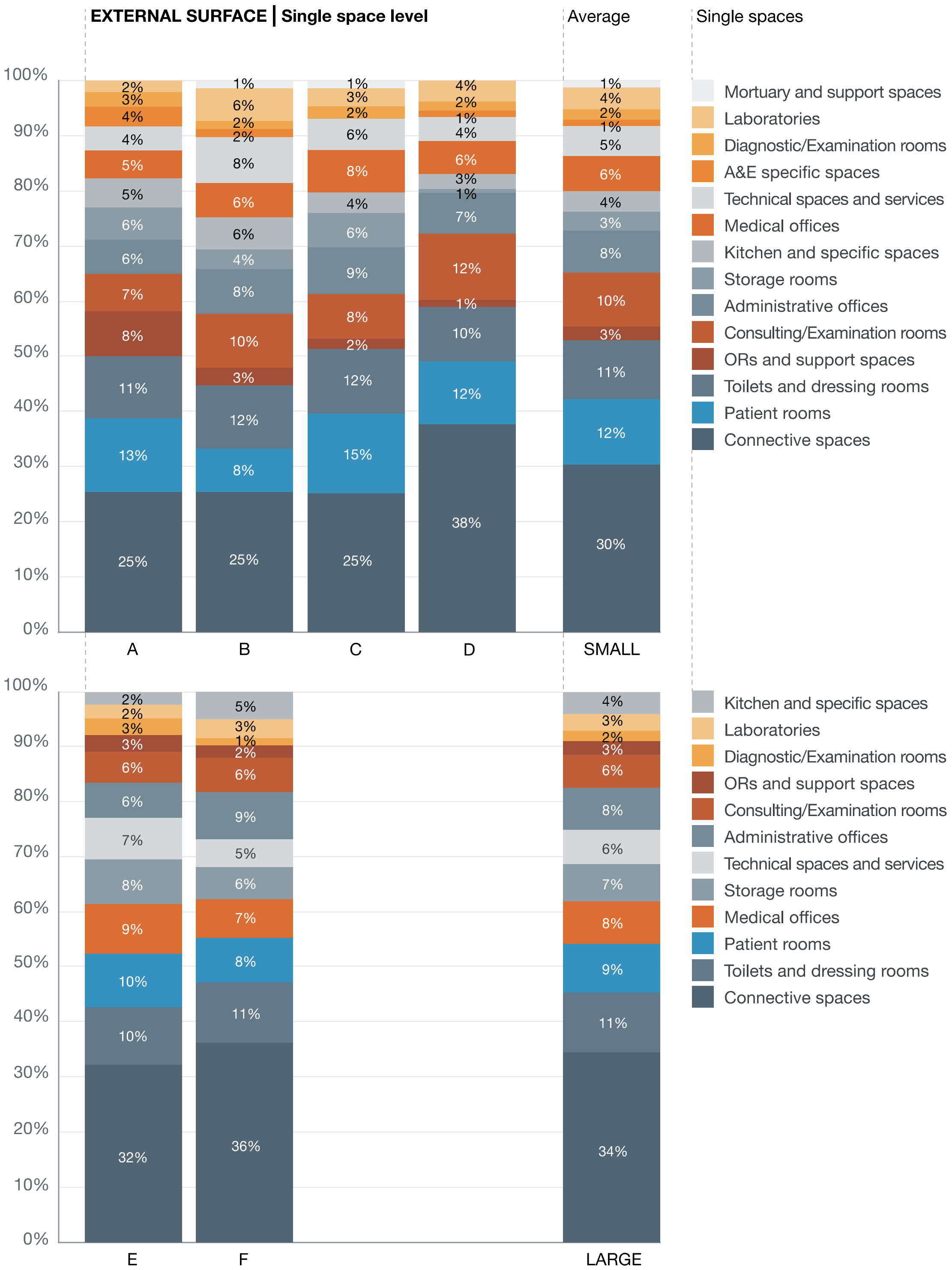


Figure 3.8. Distribution of external surface by single space

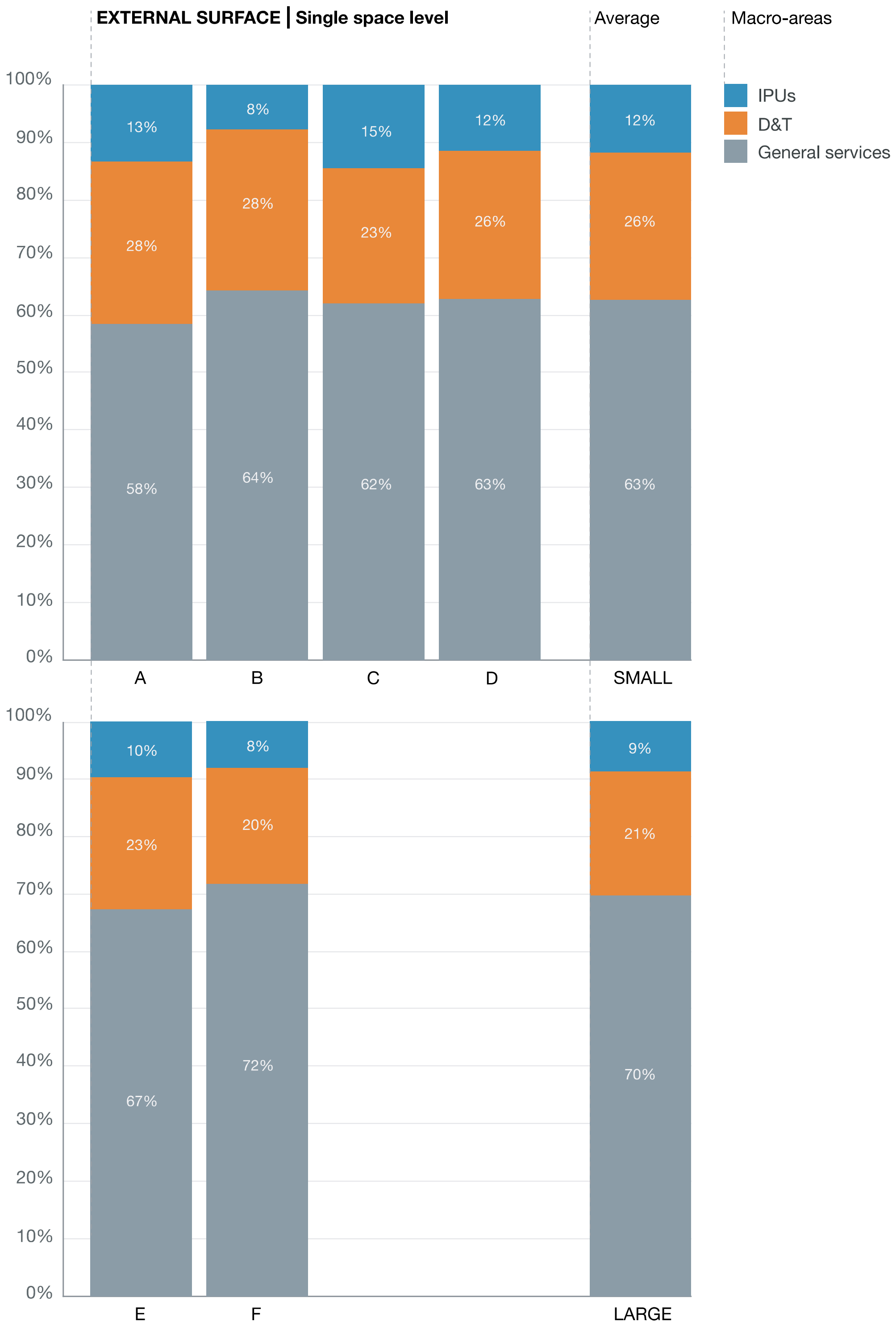


Figure 3.9. Distribution of external surface by macro-area on the base of single space level distinction

Table 3.8. Distribution of external surface of external walls at functional area level

	External surface of external walls (%)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	33	17	30	28	36	35
A&E	1	2	8	3	0	1
OPD	15	23	5	18	8	7
Diagnostic imaging	6	1	3	3	9	4
Laboratories	2	8	3	4	5	5
Medical offices	5	6	7	6	6	5
Operating theatres	9	6	1	6	3	6
Administrative offices	3	7	7	5	5	7
Connective spaces	9	8	15	17	13	18
Kitchens and canteens	6	5	5	2	3	3
Mortuary	0	1	0	0	1	1
Storage rooms	1	5	4	0	3	1
Technical spaces and services	5	9	6	3	5	3
Toilets and dressing rooms	5	2	5	6	4	4
Macro-Area						
IPUs	33	17	30	28	36	35
D&T	38	45	28	39	31	28
General services	29	37	42	32	33	37

Table 3.9. Distribution of external surface of external walls at functional area level in small and large hospitals

	External surface of external walls (%)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	27	35
A&E	4	2
OPD	14	8
Diagnostic imaging	3	6
Laboratories	4	5
Medical offices	6	5
Operating theatres	5	5
Administrative offices	6	6
Connective spaces	13	16
Kitchens and canteens	4	3
Mortuary	1	1
Storage rooms	3	2
Technical spaces and services	5	4
Toilets and dressing rooms	5	4
Macro-Area		
IPUs	27	35
D&T	36	30
General services	37	35

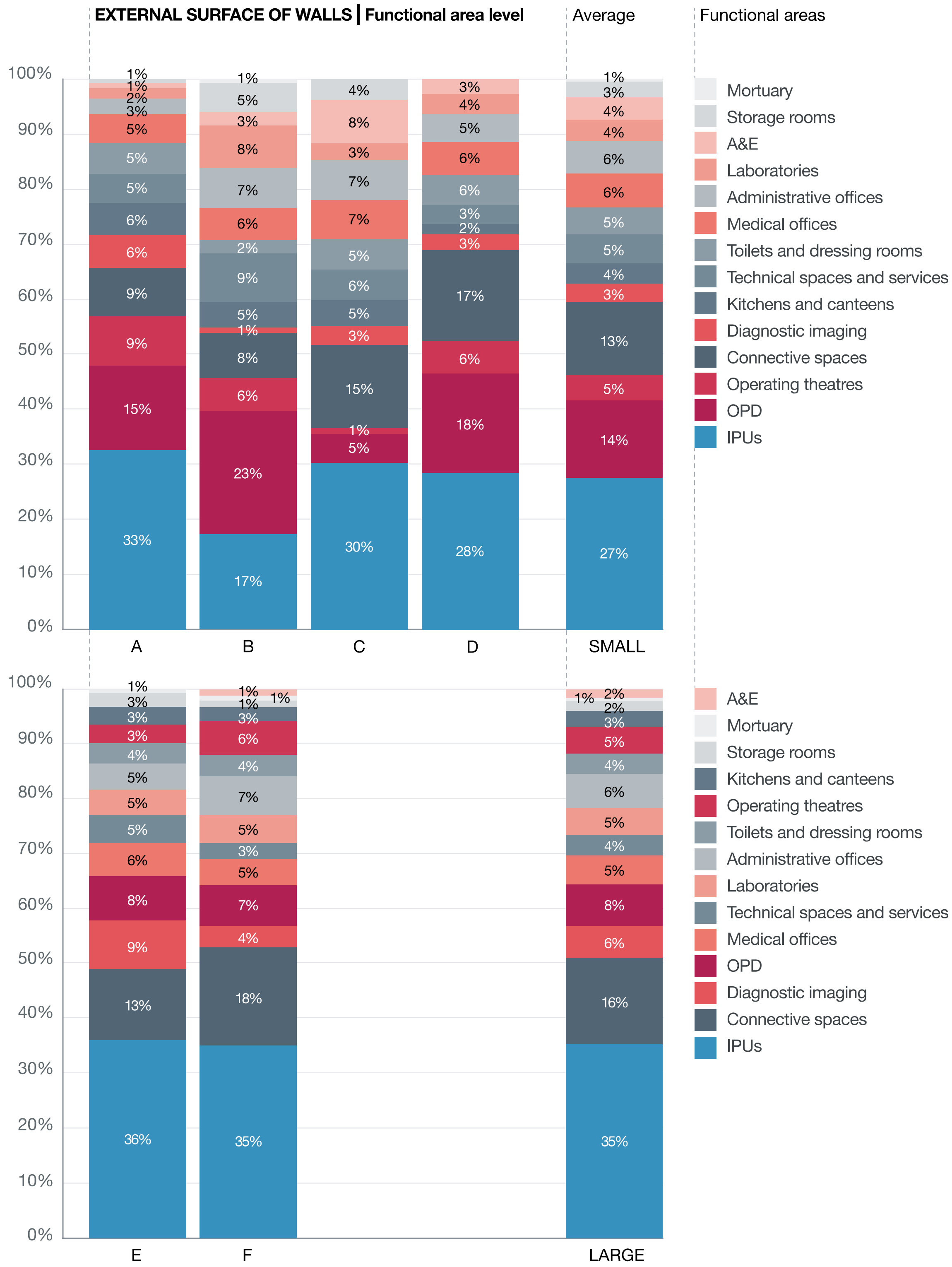


Figure 3.10. Distribution of external surface of external walls by functional area

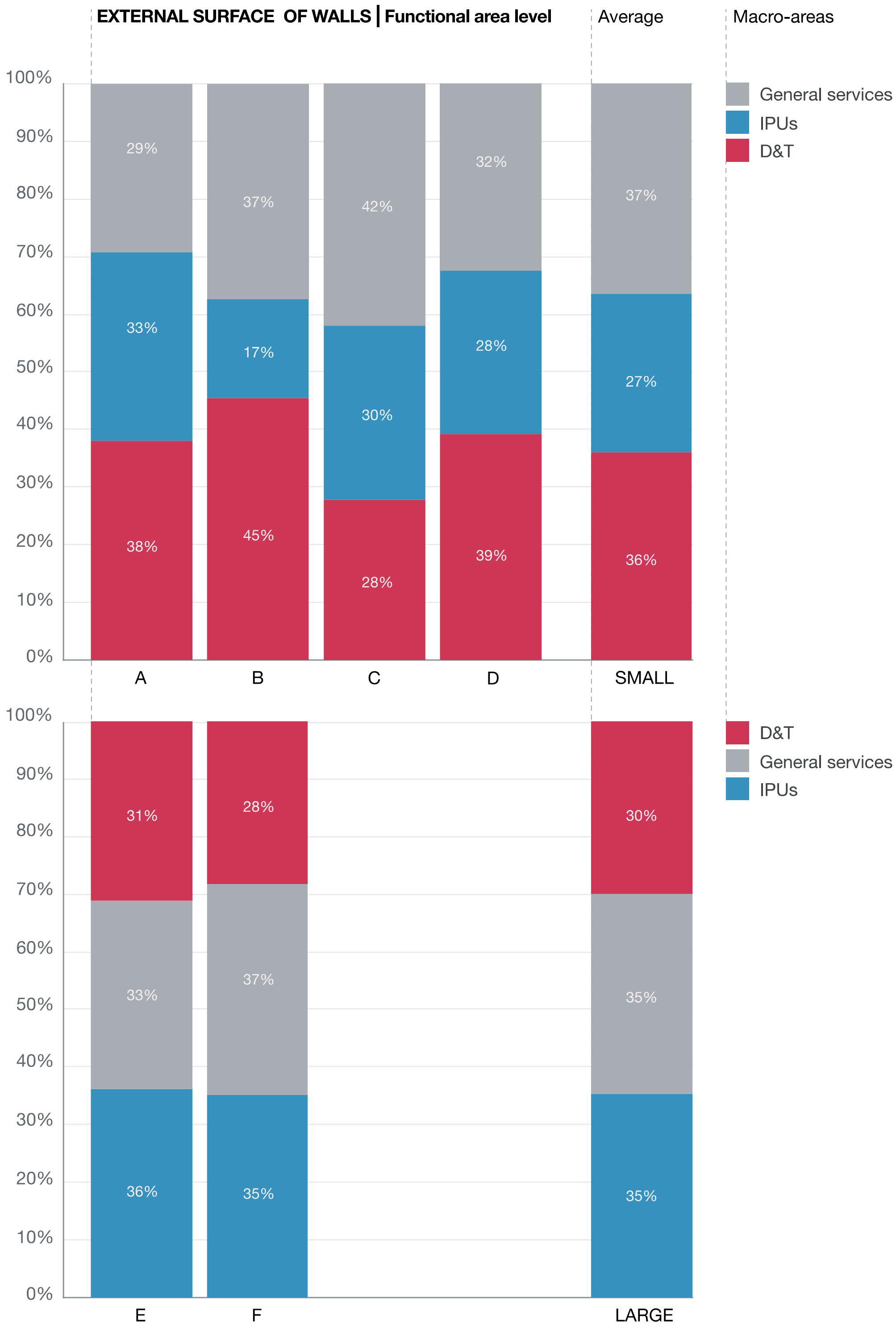


Figure 3.11. Distribution of external surface of external walls by macro-area on the base of functional area level distinction

Table 3.10. Distribution of external surface of external walls at single space level

	External surface of external walls (%)					
Single space	**A**	**B**	**C**	**D**	**E**	**F**
Patient rooms	21	12	19	16	14	15
A&E specific spaces	1	2	0	1	0	0
Consulting/Examination rooms	10	11	11	15	7	7
Diagnostic/Examination rooms	3	0	2	2	3	1
Laboratories	2	6	3	4	3	3
Medical offices	7	7	8	8	12	10
ORs and support spaces	7	2	0	2	2	2
Administrative offices	7	8	8	7	8	8
Connective spaces	15	13	18	27	24	32
Kitchen and canteen specific spaces	4	4	4	1	3	2
Mortuary and support spaces	0	1	1	0	0	0
Storage rooms	5	4	6	0	8	5
Technical spaces and services	6	9	6	5	7	4
Toilets and dressing rooms	13	20	14	11	10	9
Macro-Area						
IPUs	21	12	19	16	14	15
D&T	30	29	25	32	27	24
General services	49	59	56	52	59	61

Table 3.11. Distribution of external surface of external walls at single space level in small and large hospitals

	External surface of external walls (%)	
Single space	**Small Hospital**	**Large Hospital**
Patient rooms	17	14
A&E specific spaces	1	0
Consulting/Examination rooms	12	7
Diagnostic/Examination rooms	2	2
Laboratories	4	3
Medical offices	8	11
ORs and support spaces	2	2
Administrative offices	7	8
Connective spaces	20	29
Kitchen and canteen specific spaces	3	2
Mortuary and support spaces	1	0
Storage rooms	3	6
Technical spaces and services	6	5
Toilets and dressing rooms	14	9
Macro-Area		
IPUs	17	14
D&T	29	26
General services	54	60

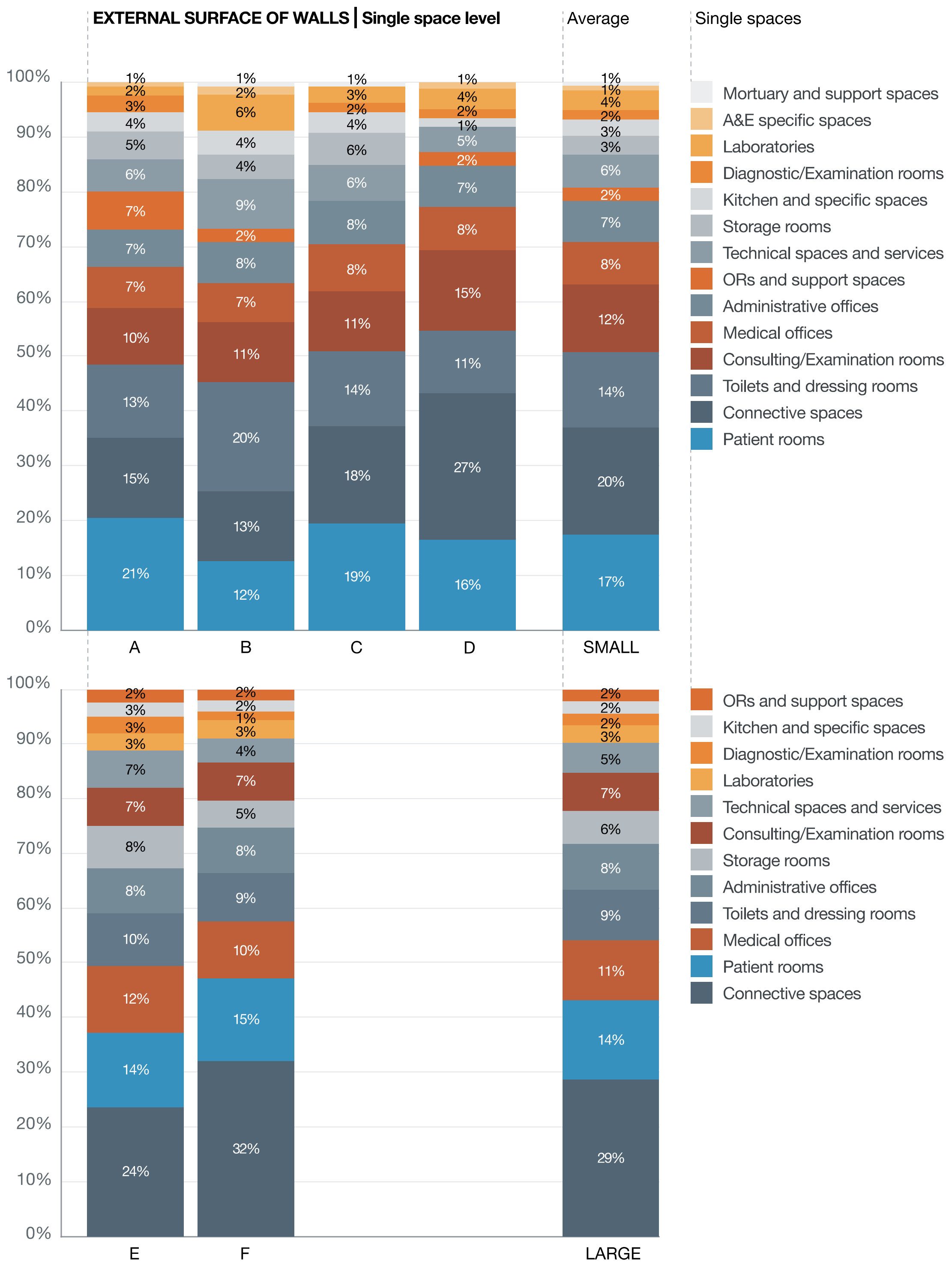


Figure 3.12. Distribution of external surface of external walls by single space

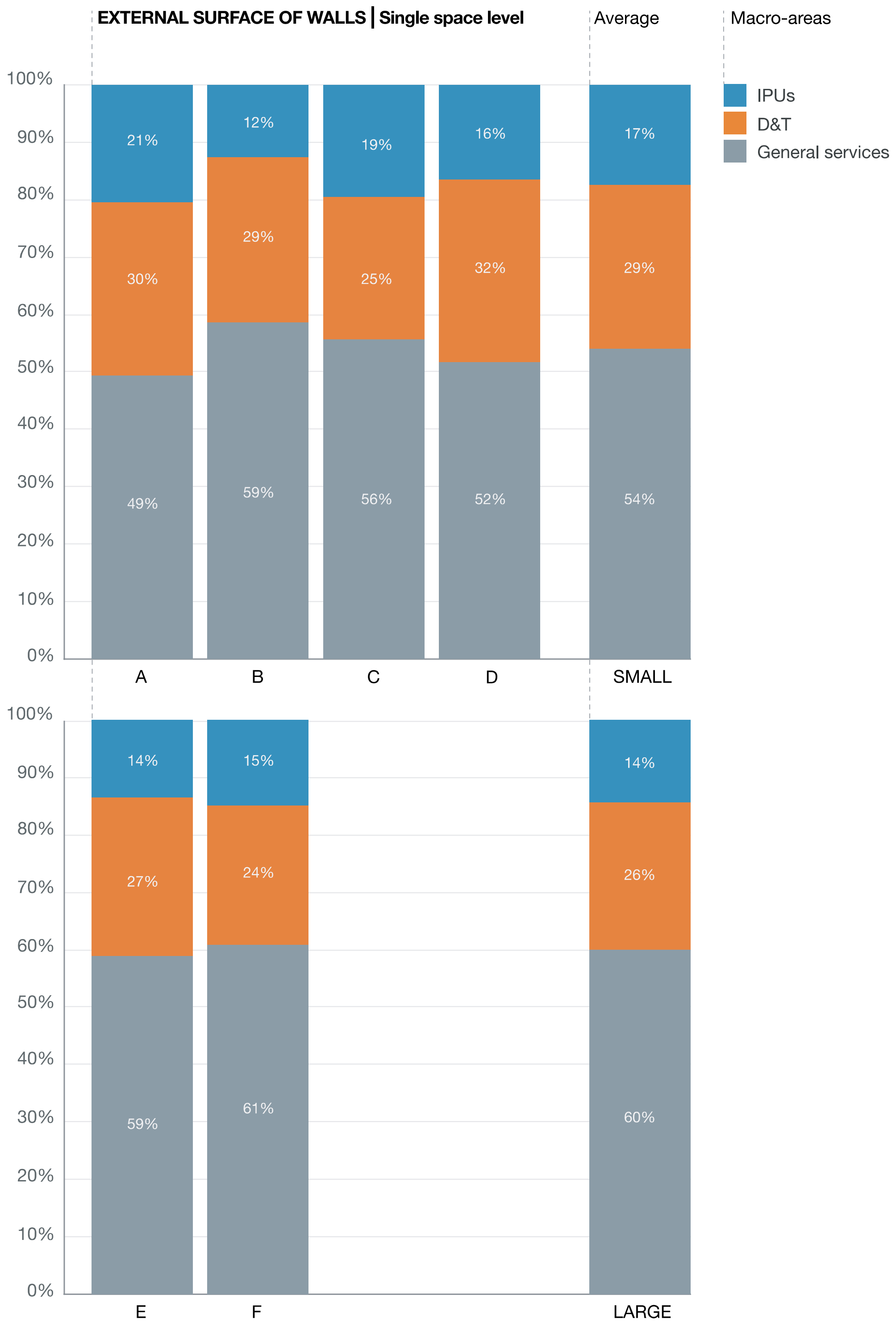


Figure 3.13. Distribution of external surface of external walls by macro-area on the base of single space level distinction

Table 3.12. Distribution of external surface of windows at functional area level

	External surface of windows (%)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	31	18	35	31	43	38
A&E	4	2	10	3	0	2
OPD	11	12	4	19	7	11
Diagnostic imaging	3	1	3	3	8	4
Laboratories	2	12	3	5	4	5
Medical offices	3	11	7	6	6	3
Operating theatres	3	2	2	3	3	6
Administrative offices	11	14	7	3	5	6
Connective spaces	20	11	14	19	13	12
Kitchens and canteens	5	4	3	3	3	6
Mortuary	0	0	0	0	0	0
Storage rooms	2	3	2	0	2	1
Technical spaces and services	4	5	5	2	4	3
Toilets and dressing rooms	2	5	4	2	3	2
Macro-Area						
IPUs	31	18	35	31	43	38
D&T	26	40	29	39	28	31
General services	43	42	36	30	29	31

Table 3.13. Distribution of external surface of windows at functional area level in small and large hospitals

	External surface of windows (%)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	30	40
A&E	5	2
OPD	12	9
Diagnostic imaging	3	5
Laboratories	5	5
Medical offices	7	4
Operating theatres	2	5
Administrative offices	7	6
Connective spaces	16	12
Kitchens and canteens	3	5
Mortuary	0	0
Storage rooms	2	1
Technical spaces and services	4	3
Toilets and dressing rooms	3	2
Macro-Area		
IPUs	30	40
D&T	34	30
General services	36	30

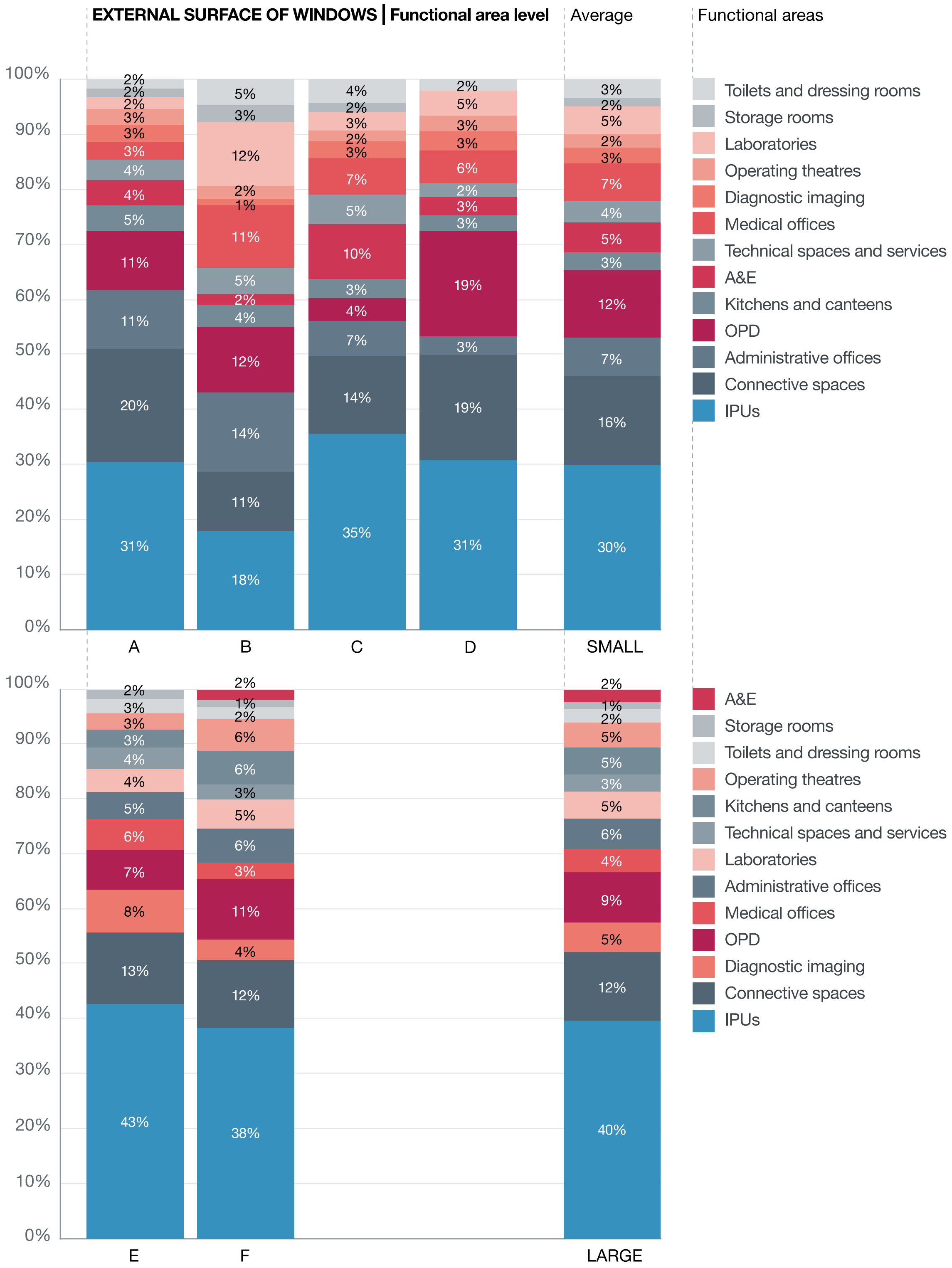


Figure 3.14. Distribution of external surface of windows by functional area

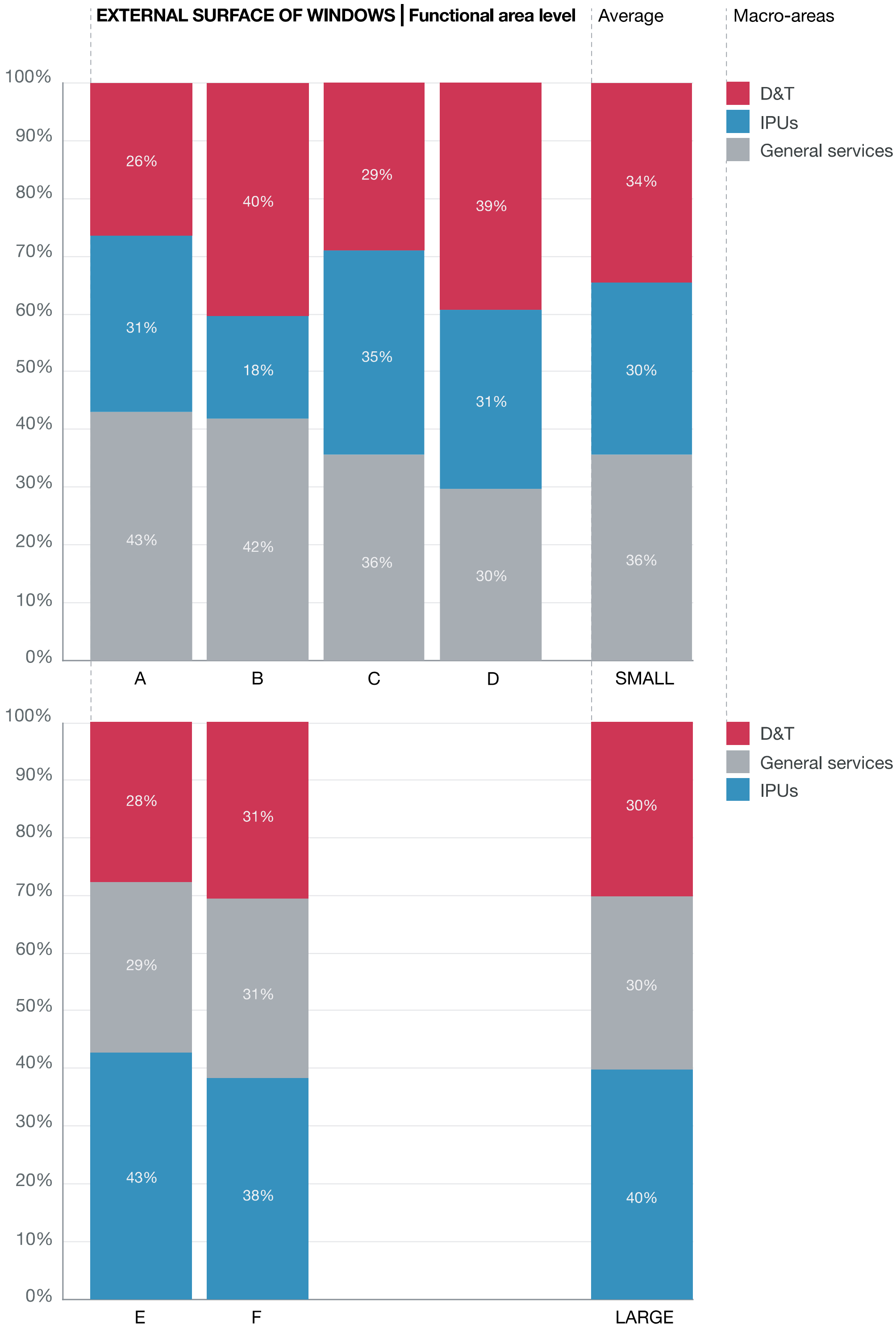


Figure 3.15. Distribution of external surface of windows by macro-area on the base of functional area level distinction

Table 3.14. Distribution of external surface of windows at single space level

	External surface of windows (%)					
Single space	**A**	**B**	**C**	**D**	**E**	**F**
Patient rooms	16	14	20	18	13	16
A&E specific spaces	4	1	1	1	0	0
Consulting/Examination rooms	7	12	10	14	7	10
Diagnostic/Examination rooms	1	0	1	2	2	2
Laboratories	2	10	3	5	3	4
Medical offices	6	13	9	9	12	12
ORs and support spaces	2	1	1	1	2	2
Administrative offices	13	14	8	6	8	9
Connective spaces	28	16	17	30	30	22
Kitchen and canteen specific spaces	4	4	3	2	3	5
Mortuary and support spaces	0	0	0	0	0	0
Storage rooms	5	3	4	0	5	6
Technical spaces and services	4	5	7	4	6	5
Toilets and dressing rooms	8	8	16	7	9	8
Macro-Area						
IPUs	16	14	19	18	13	16
D&T	22	37	25	31	26	30
General services	62	49	56	51	61	54

Table 3.15. Distribution of external surface of windows at single space level in small and large hospitals

	External surface of windows (%)	
Single space	**Small Hospital**	**Large Hospital**
Patient rooms	17	15
A&E specific spaces	1	0
Consulting/Examination rooms	12	9
Diagnostic/Examination rooms	1	2
Laboratories	5	4
Medical offices	9	12
ORs and support spaces	1	2
Administrative offices	9	8
Connective spaces	23	25
Kitchen and canteen specific spaces	3	4
Mortuary and support spaces	0	0
Storage rooms	2	5
Technical spaces and services	5	5
Toilets and dressing rooms	10	8
Macro-Area		
IPUs	17	15
D&T	29	28
General services	54	57

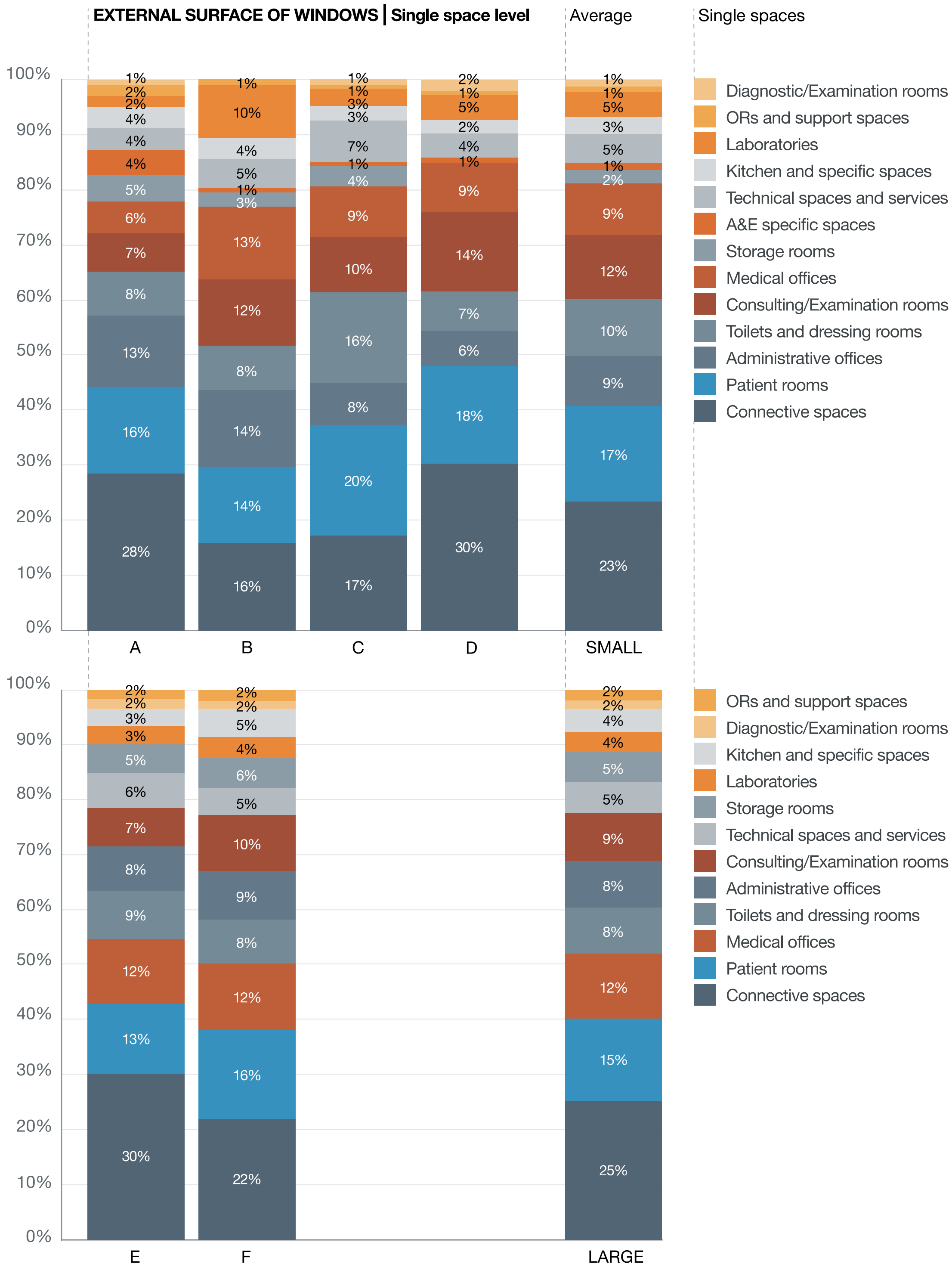


Figure 3.16. Distribution of external surface of windows by single space

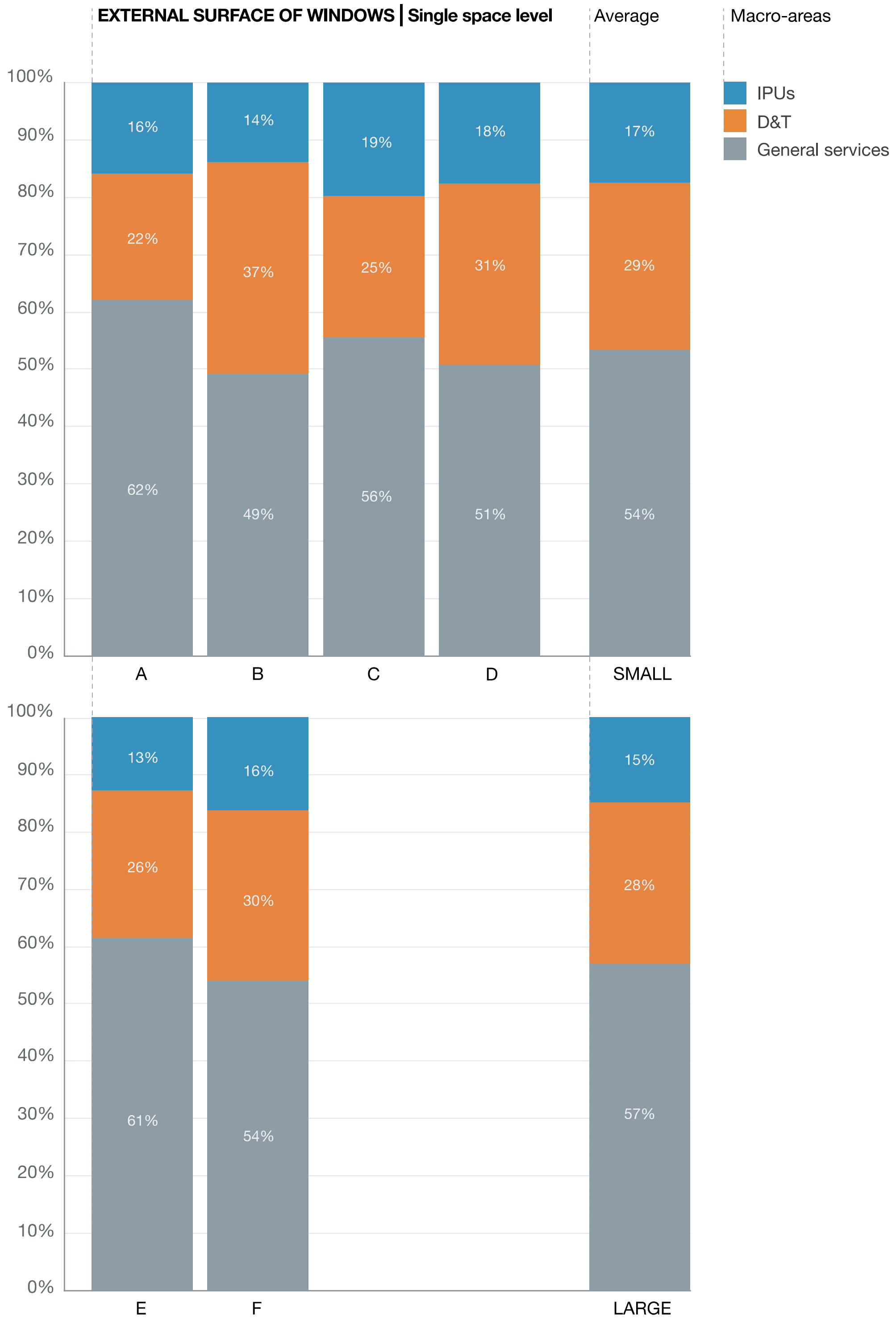


Figure 3.17. Distribution of external surface of windows by macro-area on the base of single space level distinction

The analysis of the data regarding the distribution of the external surface in relation to the building envelope components outlines the same values for hospitals with a compact form and for those with an articulated form, regardless of the year of construction (Tables 3.3). In the first ones the glazing area is responsible for 10% of the total external surface, while in the second ones windows contribute only 8% of the external surface, showing that the more articulated distribution was not used to increase the window-to-wall ratio, but only resulted in a greater opaque external surface. Furthermore, the values reported are lower than those outlined in the study of the IDL. This discrepancy could be due to the difference between the period to which the case studies date back and the period in which the American work was developed (2010), but also to the fact that the American work is based on prototype buildings, thus underlining the importance of the exclusive use of measurement data collected from existing and operative hospitals to avoid the inaccuracies that can come from building simulation methods.

The distribution of the external surface by considering the space type follows a very similar trend to the conditioned floor area. IPUs at functional area level and patient rooms at single space level are the first and the second space type, respectively, to contribute to hospital external surface, again followed and preceded by connective spaces (from Table 3.4 to 3.7 and from Figure 3.6 to 3.9). In order to aid a deeper understanding of these results is important to underline that IPUs and specifically patient rooms, requiring access to daylight more than other hospital spaces, are traditionally located along the building perimeter, around the core zones destined for technical and storage spaces.

In addition to these type of spaces, and similarly to the analysis of the conditioned floor area, consulting and examination rooms at single space level have a rather significant impact on the external surface distribution, but, in this case, an important role is played also by medical and administrative offices, both at single space level and at functional area level. Indeed, despite requiring a lower amount of daylight than patient rooms, these spaces need to have daylight access anyway and therefore are located along the building perimeter.

For the same reason, at functional area level, also operating theatres and outpatient department, which quite contribute to the conditioned floor area, have a considerable impact on the external surface distribution (from Table 3.4 to 3.7 and from Figure 3.6 to 3.9).

4 Energy analysis

The fourth phase of the work was focused on the evaluation of actual annual thermal energy consumption for transmission, natural ventilation, mechanical ventilation, humidification, summer reheating, DHW and sterilisation on the base of data and information gathered through the use of sensors, the analysis of primary sources and of building plants. More in detail, heating, ventilation and humidification energy consumption were calculated under dynamic conditions, on the base of hourly data of outdoor air temperature and relative humidity, in order to achieve more robust and reliable energy consumption data compared to those obtained from theoretical energy demand (see Figure 2.3).

4.1 Data collected and measurements

In the following tables are reported data and information gathered to assess thermal energy consumption of the six hospitals examined.

Table 4.1. Climate data of the hospitals analysed

Hospital	Climate zone	HDD (°C)	Heating period (days)
A	E	2,431	183
B	E	2,315	183
C	E	2,194	183
D	E	2,329	183
E	E	2,259	183
F	E	2,259	183

Table 4.2. Design climatic conditions in winter

Outdoor		Indoor	
T (°C)	RH (%)	T (°C)	RH (%)
-5°	80	20	50

Table 4.3. Thermal transmittance of the components of the building envelope

	Average thermal transmittance ($W \cdot m^{-2}K^{-1}$)			
Hospital	**External wall**	**Window**	**External roof**	**Ground floor slab**
A (pre-ins.)	1.79	3.40	1.60	0.33
(post-ins.)	0.54	3.40	1.60	0.33
B	1.63	3.33	0.51	0.40
C	2.03	3.45	1.71	0.36
D	1.89	3.31	0.06	0.31
E	1.62	3.66	1.38	0.59
F	0.99	2.94	0.38	0.87

Table 4.4. Type of heating system (HS) and heating terminal unit

Hospital	**all-air system (AHU)**	**HS with radiators**	**HS with radiant ceiling panels**	**HS with fan coil units**	**HS with aerotherms**	**HS with convectors**
A	O	O		O		
B	O	O				
C	O	O		O		
D	O	O		O		
E	O	O			O	O
F	O	O	O			

Table 4.5. Efficiencies of the heating systems

Hospital	**Combustion efficiency**	**Distribution efficiency**	**Average global efficiency**
A	0.94	0.96	0.76
B	0.94	0.96	0.76
C	0.94	0.96	0.76
D	0.94	0.86	0.76
E	0.94	0.76	0.76
F	0.94	0.86	0.76

Efficiencies values of the heating systems are outlined in Table 4.5. For hospital heating systems combustion efficiency is usually very high, reaching about 0.94. The values of distribution efficiency, reported in Table 4.5, were acquired from the managers of the facilities analysed, while regarding regulation and emission efficiency, their values were obtained from literature, where the product of the last three types of efficiency is on average 0.85. Therefore, global efficiency of the six hospitals analysed, obtained from the product of all the efficiencies mentioned above, was assumed equal to 0.76.

Air flow rates of the AHUs of the hospitals examined are reported in Table 4.6. For hospital D, E and F, data are the result of instrumental measurements, while for hospital A, B and C, air flow rates were collected from specifications reported in machine data plate or from direct evaluation of duct dimensions. As outlined by the values reported, for hospital D, E and F significant discrepancies were found between the nominal and the measured air flow rate (up to 30%), uncovering that mechanical ventilation no more complied with design conditions. This underlines the importance to always conduct instrumental measurements of AHUs' air flow rates in order to verify the actual volume of air introduced in hospital spaces.

Table 4.6. Air flow rate of the AHUs

	AHUs' air flow rate	
Hospital	**Nominal air flow rate ($m^3 \cdot h^{-1}$)**	**Inlet air flow rate ($m^3 \cdot h^{-1}$)**
A (pre-ins.)	9,491	9,491
(post-ins.)	9,491	9,491
B	31,217	31,217
C	60,640	60,640
D	92,950	76,136*
E	303,600	204,526*
F	531,395	486,060*

* measured

Taking into consideration heat recovery systems, it was found that, for hospital D and F, there were functional areas including some zones served by an AHU equipped with heat recovery and, within the same functional area, other zones served by an AHU without this system. Furthermore, for hospital E, available data did not allow to provide information regarding the presence of heat recovery, as outlined in Table 4.7. For these reasons, heat recovery units were not considered in energy consumption evaluation.

Table 4.7. AHUs with (O) and without (–) heat recovery system

	AHUs' heat recovery system					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs		O	–	O / –	unknown	O / –
A&E		–	–	O / –	unknown	O
OPD			–	O / –	unknown	O / –
Diagnostic imaging	–	–		O	unknown	O / –
Laboratories				O	unknown	O / –
Medical offices				–	unknown	O / –
Operating theatres	O	O	–	O –	unknown	O / –
Administrative offices					unknown	O / –
Connective spaces					unknown	
Kitchens and canteens		–			unknown	

Mortuary	unknown	O
Storage rooms	unknown	
Technical spaces and services	unknown	O
Toilets and dressing rooms	unknown	O / –

The supposed hospital daily demand for DHW, reported in Table 4.8, was evaluated by considering 32 $l \cdot day^{-1} bed^{-1}$ for hospital A and B and 35 $l \cdot day^{-1} bed^{-1}$ for hospital C, D, E and F.

Table 4.8. Assumed hospital daily demand for DHW

Hospital	daily demand for DHW ($l \cdot day^{-1}$)
A	2,900
B	3,000
C	3,990
D	7,735
E	15,000
F	30,000

Table 4.9. Data regarding steam sterilisers of hospital E and F

n. of sterilisers	mass flow rate per steriliser ($kg \cdot h^{-1}$)	operating hours per year ($h \cdot y^{-1}$)
4	100	4680

4.2 Dynamic thermal energy consumption evaluation

4.2.1 Dynamic calculation of energy consumption for transmission, ventilation and humidification

A numerical model for the dynamic assessment – for the heating period – of thermal energy consumption for transmission, natural ventilation, mechanical ventilation and humidification was developed and implemented in Microsoft Excel. The model allowed to automatically calculate energy consumption at functional area level by entering:

- hourly values of outdoor air temperature and relative humidity for winter period of the year considered;
- combustion, distribution, regulation and emission efficiency;
- theoretical energy demand for transmission of each functional area;
- air flow rate of the AHUs related to each functional area.

Theoretical energy demand was transformed in actual hourly energy needs ($\dot{Q}_A|_{hourly}$). The sum of these ones, considered for the whole heating period (extended from 1 October to 30 April), allowed to evaluate actual seasonal energy demand ($\dot{Q}_A|_{seasonal}$) (Eq. 1).

Actual seasonal energy consumption ($C_A|_{seasonal}$) was calculated by dividing actual seasonal energy demand by the product of combustion (η_{comb}), distribution ($\eta_{distrib}$), regulation (η_{reg}) and emission (η_{em}) efficiency, as outlined by eq. (2).

$$\dot{Q}_A|_{seasonal} = \sum_{i=1\,Oct}^{30\,Apr} \dot{Q}_A|_{hourly_i}\,[kWh] \qquad \left[\frac{kWh}{yr}\right] \tag{1}$$

$$C_A|_{seasonal} = \frac{\dot{Q}_A|_{seasonal}\,[kWh/yr]}{\eta_{comb}\,\eta_{distrib}\,\eta_{reg}\,\eta_{em}} \qquad \left[\frac{kWh}{yr}\right] \tag{2}$$

The detailed description of the calculation method of hourly energy needs for each end use is reported in the following sections (from section 4.2.1.1 to 4.2.1.4).

For heating energy consumption evaluation, the numerical model also allowed to assess solar and internal heat gains in relation to the conditioned floor area of each functional area. Monthly values per unit floor area provided by the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (Corrado et al., 2016) were used, as reported in Table 4.10. The seasonal energy demand for transmission was then calculated by subtracting solar and internal heat gains from it. Differently from the other components, solar and internal energy gains were not analysed in detail as their contribution to the overall energy consumption is decisively small.

Table 4.10. Monthly contribution of solar and internal heat gains

	Solar and internal heat gains	
Month	**MJ·(m2month)-1**	**kWh·(m2month)-1**
October	20.0	5.56
November	11.0	3.06
December	10.0	2.78
January	10.0	2.78
February	14.0	3.89
March	21.0	5.83
April	25.0	6.95

4.2.1.1 Calculation of theoretical energy demand and hourly energy needs for transmission

The assessment of theoretical energy demand for transmission ($\dot{Q}_{tr_{TH}}$) of each functional area was conducted with TerMus software (ACCA) for hospital A, E and F, and with MC Impianti 11300 software (AERMEC), for hospital B, C and D. The methodological approach, as well as the equations used, were the same for both the software.

Except for outdoor design climatic conditions, automatically considered by the software in relation to the city where the hospital is located, it was necessary to provide the program with some technical data at building level, like:

- the description of the building envelope components (internal and external walls, ground floor, roof, windows, etc.), according to which the software calculated thermal transmittance of each element. When the available data did not allow to provide this information with certainty, the composition of the building envelope elements was supposed on the base of the construction techniques usually adopted when the hospital was built;
- the definition of the types of heating system and ventilation, if natural or mechanical;
- the different thermal zones, in relation to the functional areas.

Once completed this first phase, a series of data regarding each single space was entered into the program, like:

- the function;
- building floor;
- conditioned floor area and volume;
- orientation of the building envelope components;
- indoor design climatic conditions
- type of heating system and ventilation;
- infiltration rate and air change rate per hour (ACH).

For the sake of completeness, the results obtained, reported in Appendix B, were elaborated both at functional area level (table B.1) and at single space level (table B.2). However, as hospital energy analysis was conducted in relation to functional areas, only the findings elaborated at functional area level were used for energy consumption assessment.

Actual hourly energy needs for transmission ($\dot{Q}_{tr_A}|_{hourly}$) of each functional area were calculated by using the numerical model developed in Microsoft Excel, which implemented eq. (3). Theoretical energy demand for transmission (previously assessed by the software) was divided by the difference between winter indoor and outdoor design temperature, equal to 25°C (used by the software for theoretical energy demand calculation), and multiplied by the difference between indoor design temperature and the measured hourly outdoor air temperature ($\Delta T|_{hourly}$) (Eq. 4).

$$\dot{Q}_{tr_A}|_{hourly} = \frac{\dot{Q}_{tr_{TH}}\,[kW]}{(20+5)[°C]}\ \Delta T|_{hourly}[°C] \qquad [kWh] \qquad (3)$$

$$\Delta T|_{hourly} = 20[°C] - T_{out}|_{hourly}[°C] \qquad [°C] \qquad (4)$$

Equations (3) and (4) underline that the aim of the work is the development of a simplified numerical model for the evaluation of thermal energy consumption. Indeed, it may be objected that eqs. (3) and (4) can be applied only to the components of the building envelope that separate indoor from outdoor environments, but not to those components dividing indoor from unheated spaces or indoor spaces from the ground. However, the contribution of these last two types of components to the overall energy consumption is decisively small, thus the related error can be considered negligible.

4.2.1.2 Calculation of hourly energy needs for natural ventilation

Taking into consideration natural ventilation, the numerical model allowed to directly evaluate hourly energy needs $\dot{Q}_{Nve_A}|_{hourly}$. For each functional area, the model was informed with the related air change rate per hour for natural ventilation ACH_{Nve} and the related naturally ventilated volume V_{Nve}. Hourly energy needs were calculated on the base of eq. (5).

$$\dot{Q}_{Nve_A}|_{hourly} = ACH_{Nve}\left[\frac{1}{h}\right]\ V_{Nve}[m^3]\ \rho_{air}\left[\frac{kg}{m^3}\right]\ cp_{air}\left[\frac{kJ}{kg°C}\right]\ \Delta T|_{hourly}[°C]\ \frac{1}{3600}\left[\frac{kWh}{kJ}\right] \qquad [kW] \qquad (5)$$

where ρ_{air} is density of air, equal to 1,2 kg·m-3 and cp_{air} is the specific heat capacity of air, equal to 1,005 kJ·(kg°C)-1. Air flow rates for natural ventilation related to each functional area are reported in Appendix B, table B.7.

4.2.1.3 Calculation of hourly energy needs for mechanical ventilation

As for actual hourly energy needs for natural ventilation, those for mechanical ventilation $\dot{Q}_{Nve_A}|_{hourly}$ were calculated with the numerical model implemented in Microsoft Excel. For each functional area, the model was informed with the air flow rate $\dot{V}$ of the related AHU and calculated hourly energy needs on the base of eq. (6). Air flow rate of the AHUs related to each functional area are reported in Appendix B, table B.8.

$$\dot{Q}_{Mve_A}|_{hourly} = \dot{V}\left[\frac{m^3}{h}\right]\ \rho_{air}\left[\frac{kg}{m^3}\right]\ cp_{air}\left[\frac{kJ}{kg°C}\right]\ \Delta T|_{hourly}[°C]\ \frac{1}{3600}\left[\frac{kWh}{kJ}\right] \qquad [kWh] \qquad (6)$$

4.2.1.4 Calculation of hourly energy needs for humidification

The assessment of hourly energy needs for humidification was carried out by the numerical model according to the following equation:

$$\dot{Q}_{HUM_A}|_{hourly} = \dot{V}\left[\frac{m^3}{h}\right]\ \rho_{air}\left[\frac{kg}{m^3}\right]\ \frac{\Delta y|_{hourly}\left[\frac{g}{kg_{dry\ air}}\right]}{1000}\ r\left[\frac{kcal}{kg}\right]\ \frac{1}{860}\left[\frac{kWh}{kcal}\right] \qquad [kWh] \qquad (7)$$

where r is the latent heat of vaporisation and is equal to 540 kcal·kg^{-1}, $\Delta y|_{hourly}$ is the difference between humidity ratio of indoor design climatic condition, equal to 7,27 g·(kg$_{dry\ air}$)$^{-1}$, and hourly outdoor humidity ratio (Eq.8), calculated by the numerical model on the base of hourly values of outdoor air temperature and relative humidity.

$$\Delta y|_{hourly} = 7{,}27\left[\frac{g}{kg_{dry\ air}}\right] - y_{out}|_{hourly}\left[\frac{g}{kg_{dry\ air}}\right] \qquad \left[\frac{g}{kg_{dry\ air}}\right] \qquad (8)$$

4.2.2 Calculation of energy consumption for summer reheating

Likewise energy consumption for transmission, natural ventilation, mechanical ventilation and humidification, energy consumption for summer reheating was evaluated in relation to functional areas. Theoretical energy demand for summer reheating was calculated as:

$$\dot{Q}_{rehe_{TH}} = \dot{V}\left[\frac{m^3}{h}\right]\ \rho_{air}\left[\frac{kg}{m^3}\right]\ cp_{air}\left[\frac{kJ}{kg°C}\right]\ \Delta T[°C]\ \frac{1}{3600}\left[\frac{kWh}{kJ}\right] \qquad [kW] \qquad (9)$$

where $\dot{V}$ is the air flow rate of the AHU of the considered functional area and ΔT is the difference of temperature of the reheating coils, which is equal to 6 °C. Indeed, air flows out from the cooling coil in saturation conditions with a temperature of about 15-18 °C and then it is reheated up to 24 °C. Finally, air reaches a temperature of 26 °C with the contribution of internal heat gains.

Theoretical annual energy demand for summer reheating was evaluated as:

$$\dot{Q}_{rehe_{TH}}|_{annual} = \dot{Q}_{rehe_{TH}}\ [kW]\ 24\left[\frac{h}{day}\right]120\left[\frac{day}{yr}\right] \qquad \left[\frac{kWh}{yr}\right] \qquad (10)$$

considering an operation schedule of the reheating coils of 24 hours per day and 120 days per year (equal to the cooling period).

Actual annual energy consumption ($C_{rehe_A}|_{annual}$) was calculated as:

$$C_{rehe_A}|_{annual} = \frac{\dot{Q}_{rehe_{TH}}|_{annual}\left[{kWh}/{yr}\right]}{\eta_{comb}\ \eta_{distrib}\ \eta_{reg}\ \eta_{em}} \qquad \left[\frac{kWh}{yr}\right] \qquad (11)$$

4.2.3 Calculation of DHW energy consumption

Theoretical daily energy demand for DHW ($\dot{Q}_{DHW_{TH}}|_{daily}$) was evaluated as:

$$\dot{Q}_{DHW_{TH}}|_{daily} = \dot{d}\left[\frac{kg}{day}\right]\ cp_w\left[\frac{kJ}{kg°C}\right]\ (50-15)[°C]\ \frac{1}{3600}\left[\frac{kWh}{kJ}\right] \qquad \left[\frac{kWh}{day}\right] \qquad (12)$$

where $\dot{d}$ is the supposed hospital daily demand for DHW (values for each hospital considered are reported in Table 4.8), cp_w is the specific heat capacity of water, equal to 4,186 kJ·(kg°C)-1, $(50-15)°C$ is the difference between the assumed cold water supply temperature and DHW set-point temperature.

Actual annual energy consumption ($C_{DHW_A}|_{annual}$) was calculated by multiplying the theoretical daily energy demand by the number of days per year, and dividing the product obtained by the global efficiency, as outlined by eq. (13).

$$C_{DHW_A}|_{annual} = \frac{\dot{Q}_{DHW_{TH}}|_{daily}\ [kWh/day]\ 365[day/yr]}{\eta_{comb}\ \eta_{distrib}\ \eta_{reg}\ \eta_{em}} \qquad \left[\frac{kWh}{yr}\right] \qquad (13)$$

4.2.4 Calculation of energy consumption for sterilisation

The available data allowed to evaluate energy consumption for sterilisation only for hospital E and F. Theoretical hourly energy demand for sterilisation was calculated as:

$$\dot{Q}_{ster_{TH}}|_{hourly} = \left(r\left[\frac{kcal}{kg}\right] + cp_w\left[\frac{kJ}{kg°C}\right]\ (50-15)[°C]\right)\dot{m}\left[\frac{kg}{h}\right]\ n_{sterlisers} \qquad [kW] \qquad (14)$$

where $\dot{m}$ is the mass flow rate of each steam steriliser and $n_{sterlisers}$ is the number of machines used in the process. Theoretical annual energy demand was evaluated with the following equation:

$$\dot{Q}_{ster_{TH}}|_{annual} = \dot{Q}_{ster_{TH}}|_{hourly}[kW]\ \frac{h_{oper}}{yr}\left[\frac{h}{yr}\right] \qquad \left[\frac{kWh}{yr}\right] \qquad (15)$$

where $\frac{h_{oper}}{yr}$ is the number of operating hours per year. Data regarding mass flow rate, number of sterilisers and operating schedule of hospital E and F, provided by managers, are reported in Table 4.9. Actual annual energy consumption for sterilisation $C_{ster_A}|_{annual}$ was calculated as:

$$C_{ster_A}|_{annual} = \frac{\dot{Q}_{ster_{TH}}|_{annual}\ [kWh/yr]}{\eta_{comb}\ \eta_{distrib}\ \eta_{reg}\ \eta_{em}} \qquad \left[\frac{kWh}{yr}\right] \qquad (16)$$

4.3 Elaboration of energy consumption assessed in dynamic conditions

The results regarding energy consumption of the six hospitals considered, evaluated in dynamic conditions on the base of the equations outlined before (section 4.2), are reported in the following lines. For a comprehensive interpretation of the results it is necessary to underline that, when energy usage measurements were conducted and data were collected, one of the buildings composing hospital E was not occupied. Therefore, while the analysis of the hospital healthcare functions (section 3) concerns the whole complex (characterised by a conditioned floor area of 50,786 m^2 and a conditioned volume of 169,871 m^3, as reported in Table 2.4), in the energy consumption analysis all the data related to the unoccupied building were not considered and the results are related to a conditioned floor area and volume of 35,770 m^2 and 124,673 m^3 respectively. Similarly, while the analysis of the healthcare functions concerns all the spaces composing hospital F (equal to a conditioned floor area of 90,121m^2 and a conditioned volume of 291,185 m^3)(see Table 2.4), the energy consumption analysis relates only to the effectively conditioned areas, corresponding to a conditioned floor area and volume of 72,057 m^2 and 233,312 m^3 respectively.

Furthermore, on the base of the facilities' floor area, the average of the values obtained for hospitals A, B, C and D was assumed to be representative of the energy use of small structures, while for large complexes it was considered the average energy consumption of hospital E and F.

4.3.1 Thermal energy consumption

Total thermal energy consumption for the six hospitals considered is outlined in Table 4.11 and in Figure 4.1. The parameter, which includes – for the heating period – energy use for transmission, natural ventilation, mechanical ventilation and humidification, summer reheating, annual DHW and sterilisation, is expressed as energy per unit conditioned floor area per year ($kWh \cdot m^{-2}\ y^{-1}$), energy per unit volume per year ($kWh \cdot m^{-3}\ y^{-1}$) and energy per unit hospital bed per year ($MWh \cdot bed^{-1}\ y^{-1}$).

Table 4.11. Thermal energy consumption

Thermal energy consumption	**A**		**B**	**C**	**D**	**E**	**F**
	pre-ins.	**post ins.**					
($kWh \cdot m^{-2}\ y^{-1}$)	239	192	323	499	335	534	474
($kWh \cdot m^{-3}\ y^{-1}$)	76	61	120	139	124	153	146
($MWh \cdot bed^{-1}\ y^{-1}$)	9.1	7.3	21.2	35.8	19.9	51.3	52.4

Table 4.12. Average thermal energy consumption in small and large hospitals

Average thermal energy consumption	Small Hospital	Large Hospital
($kWh \cdot m^{-2}\ y^{-1}$)	349	504
($kWh \cdot m^{-3}\ y^{-1}$)	115	150
($MWh \cdot bed^{-1}\ y^{-1}$)	21.5	51.9

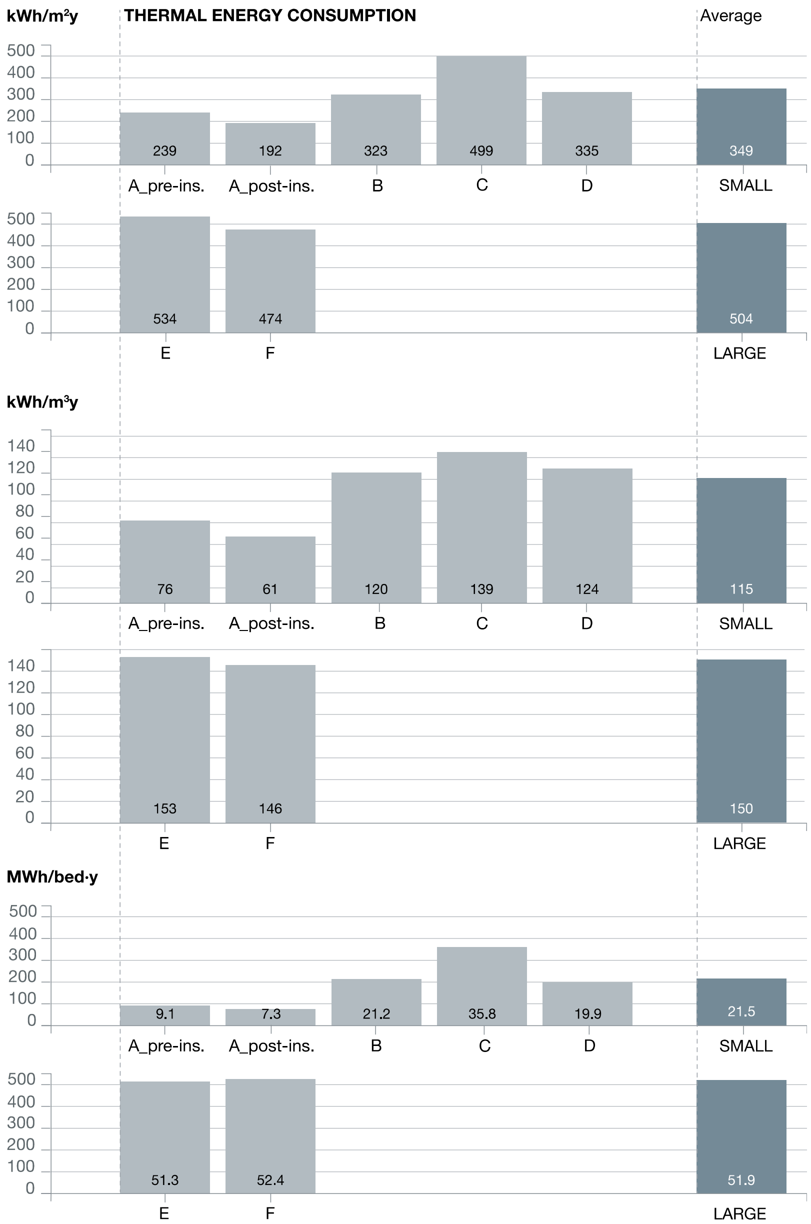


Figure 4.1. Annual thermal energy consumption per unit conditioned floor area, per unit volume and per unit hospital bed

Thermal energy consumption for the six hospitals considered was also examined in relation to functional areas, as reported in Table 4.13 and in Figure 4.2. As available data did not allow to investigate energy consumption for DHW and sterilisation in relation to the type of space, the findings illustrated below do not include these end uses.

Table 4.13. Thermal EUI in relation to the use of the spaces

	Thermal EUI* (kWh·m-2 y-1)						
Functional area	**A**		**B**	**C**	**D**	**E**	**F**
	pre-ins.	**post ins.**					
IPUs	125	67	228	447	219	401	320
A&E	319	300	409	474	821	–	558
OPD	149	95	384	392	278	589	426
Diagnostic imaging	488	433	600	326	459	494	567
Laboratories	98	63	191	963	373	564	939
Medical offices	132	71	290	474	311	426	290
Operating theatres	611	575	920	1,160	1,198	1,846	1,803
Administrative offices	255	206	164	468	132	510	307
Connective spaces	135	105	94	382	246	165	112
Kitchens and canteens	112	85	920	817	303	231	159
Mortuary	–	–	595	1,094	–	1,386	756
Storage rooms	1,425	1,396	304	519	–	411	1,185
Technical spaces and services	152	94	142	512	232	579	904
Toilets and dressing rooms	148	99	427	363	153	445	706
Macro-Area							
IPUs	125	67	228	447	219	401	320
D&T	319	273	438	578	453	672	811
General services	208	171	258	455	272	363	315
Total average	224	177	314	490	324	473	444

* without considering DHW and sterilisation

Table 4.14. Average thermal EUI in relation to the use of the spaces in small and large hospitals

	Thermal EUI* (kWh·m-2 y-1)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	255	360
A&E	506	–
OPD	301	507
Diagnostic imaging	468	531
Laboratories	406	752
Medical offices	302	358
Operating theatres	972	1,825
Administrative offices	255	409
Connective spaces	214	138
Kitchens and canteens	538	195
Mortuary	–	1,071
Storage rooms	–	798
Technical spaces and services	260	742

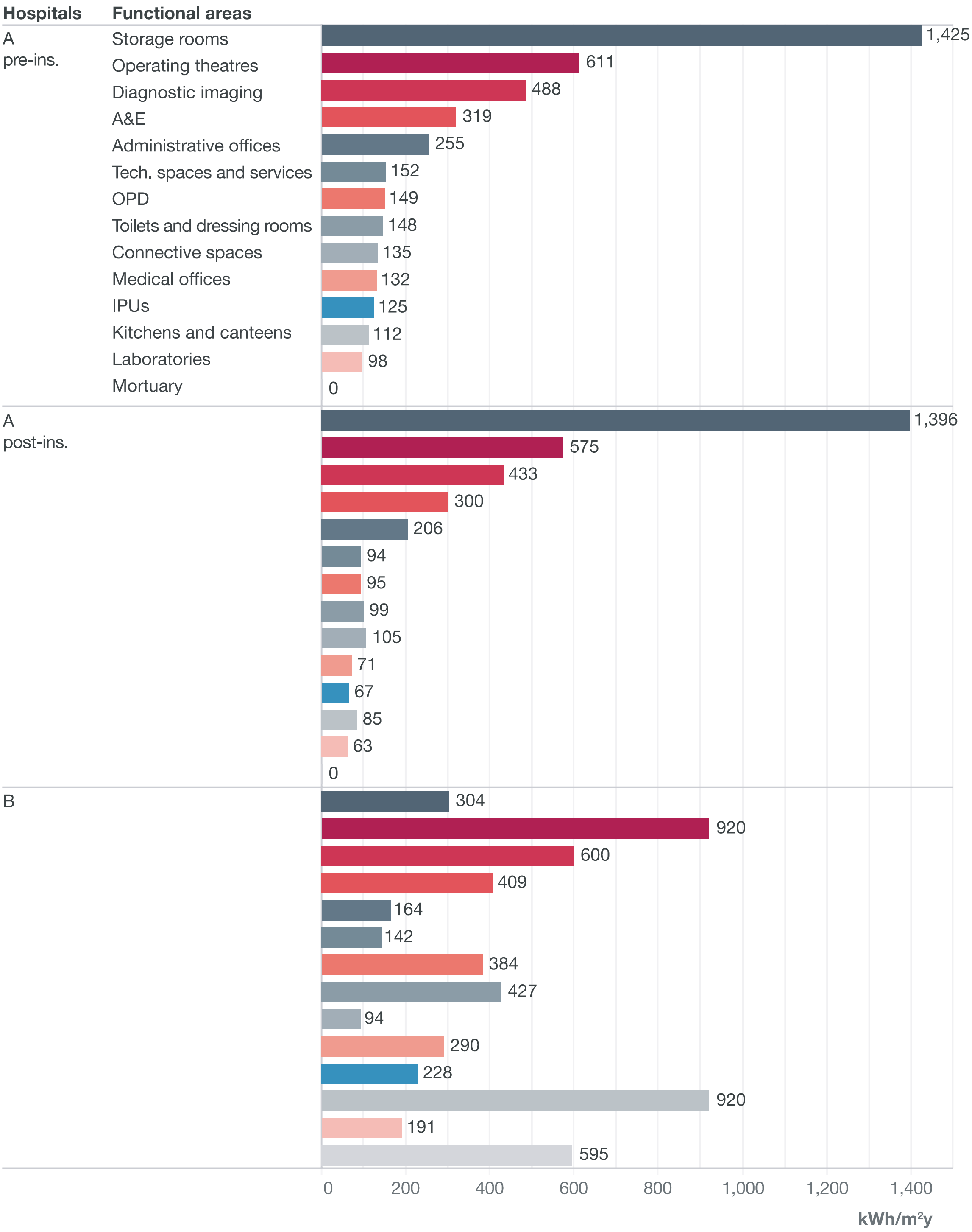
Toilets and dressing rooms	273	575
Macro-Area		
IPUs	255	360
D&T	447	742
General services	298	339
Total average	338	458

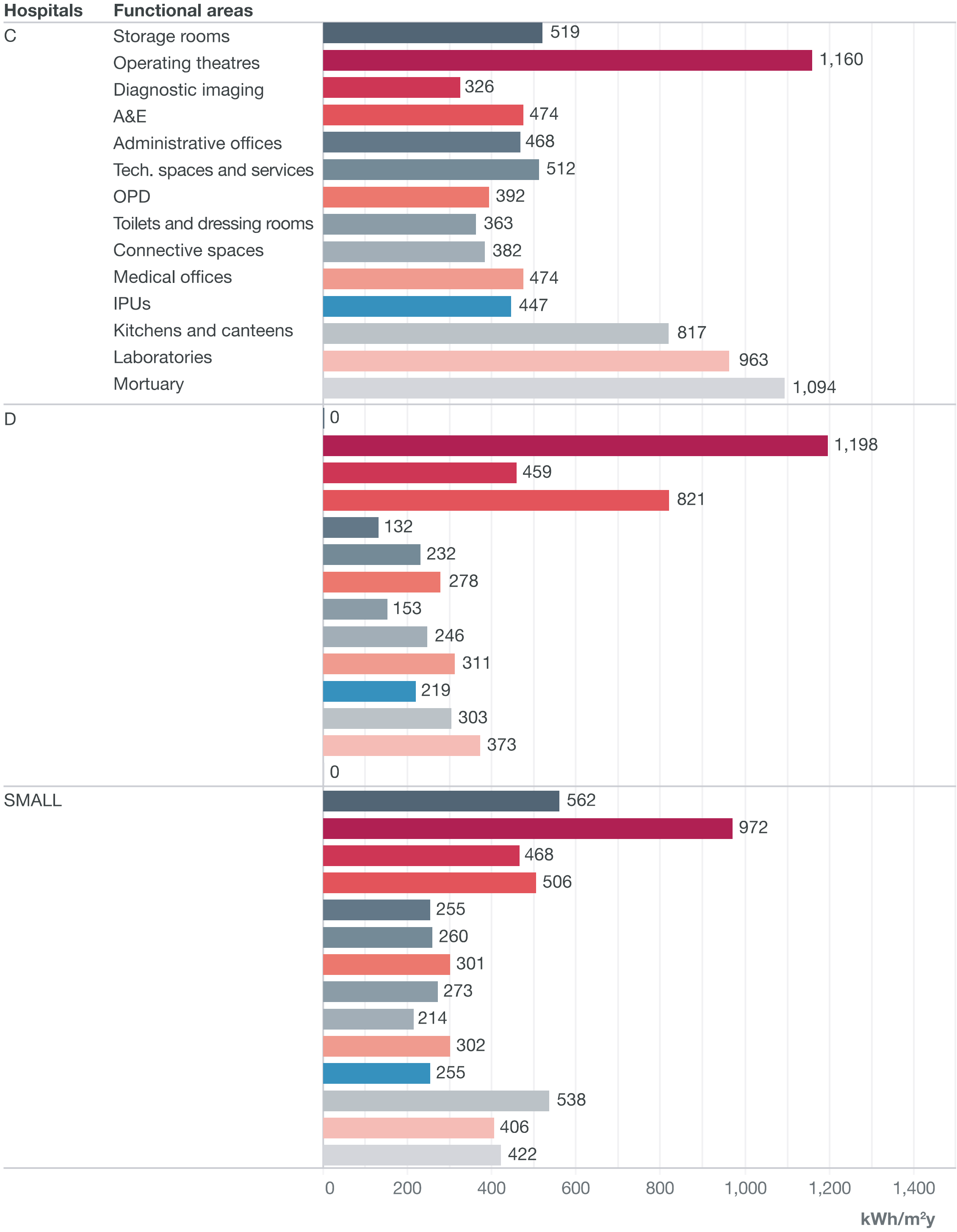
* without considering DHW and sterilisation

From the analysis of the results it was found that operating theatres are characterised by the highest EUI for all the six facilities investigated, except for hospital A. Here storage rooms are the most energy-intensive functional area, due to the fact that this type of space has to comply with strict mandatory requirements about fire safety which are often responsible for very high air change rates per hour for natural ventilation. This is outlined also in Table 5.3 where, for hospital A, storage rooms are characterised by the second highest average air change rate per hour and present the second highest energy use intensity for natural ventilation, as reported in Figure 4.6.

In small-size structures, like hospitals A, B, C and D, operating theatres are followed by A&E, diagnostic imaging and laboratories, which results to be one of the most energy-consuming functional areas also in large-size facilities like hospitals E and F, along with technical spaces and services. Indeed, for all the six hospitals analysed, findings reported at macro-area level underline that D&T is responsible for the highest energy consumption, which is comparable to the sum of the energy consumed by IPUs and general services.

THERMAL ENERGY USE INTENSITY




Hospitals
Functional areas
C
Storage rooms
Operating theatres
Diagnostic imaging
A&E
Administrative offices
Tech. spaces and services
OPD
Toilets and dressing rooms
Connective spaces
Medical offices
IPUs
Kitchens and canteens
Laboratories
Mortuary
519
1,160
326
474
468
512
392
363
382
474
447
817
963
1,094
D
0
1,198
459
821
132
232
278
153
246
311
219
303
373
0
SMALL
562
972
468
506
255
260
301
273
214
302
255
538
406
422
0
200
400
600
800
1,000
1,200
1,400
kWh/m²y

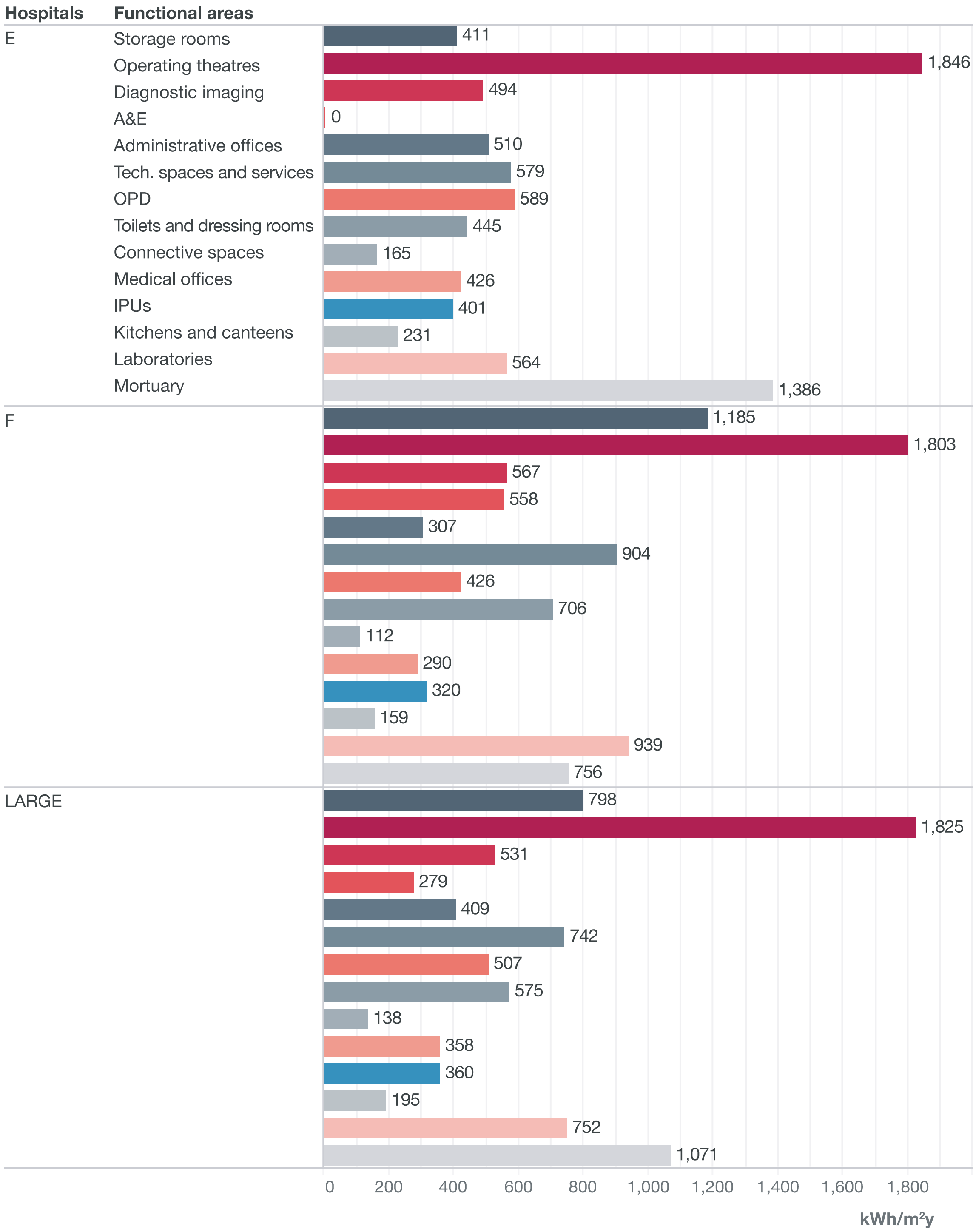


Figure 4.2. Thermal EUI in relation to the use of the spaces

4.3.2 Distribution of thermal EUI by end use

A further elaboration of the results was focused on the analysis of hospital energy consumption in relation to end uses, as presented in Table 4.15, Table 4.16 and in Figure 4.3. A comparative analysis of the data allowed to develop the observations reported in the following lines.

Table 4.15. Thermal EUI by end use

	Thermal EUI (kWh·m-2 y-1)						
Building service	**A**		**B**	**C**	**D**	**E**	**F**
	pre-ins.	**post ins.**					
Transmission	93	45	78	132	77	138	70
Ventilation:							
- natural ventilation	45	45	76	129	49	31	30
- mechanical ventilation	67	67	124	177	153	172	208
- humidification	–	–	–	–	–	81	84
Summer reheating	20	20	36	52	44	50	52
DHW	15	15	9	8	11	9	8
Sterilisation	–	–	–	–	–	52	23
Total average	239	192	323	499	335	534	474

Table 4.16. Average thermal EUI by end use in small and large hospitals

	Thermal EUI (kWh·m-2 y-1)	
Building service	**Small Hospital**	**Large Hospital**
Transmission	95	104
Ventilation:		
- natural ventilation	75	31
- mechanical ventilation	130	190
- humidification	–	83
Summer reheating	38	51
DHW	11	8
Sterilisation	–	37
Total average	349	504

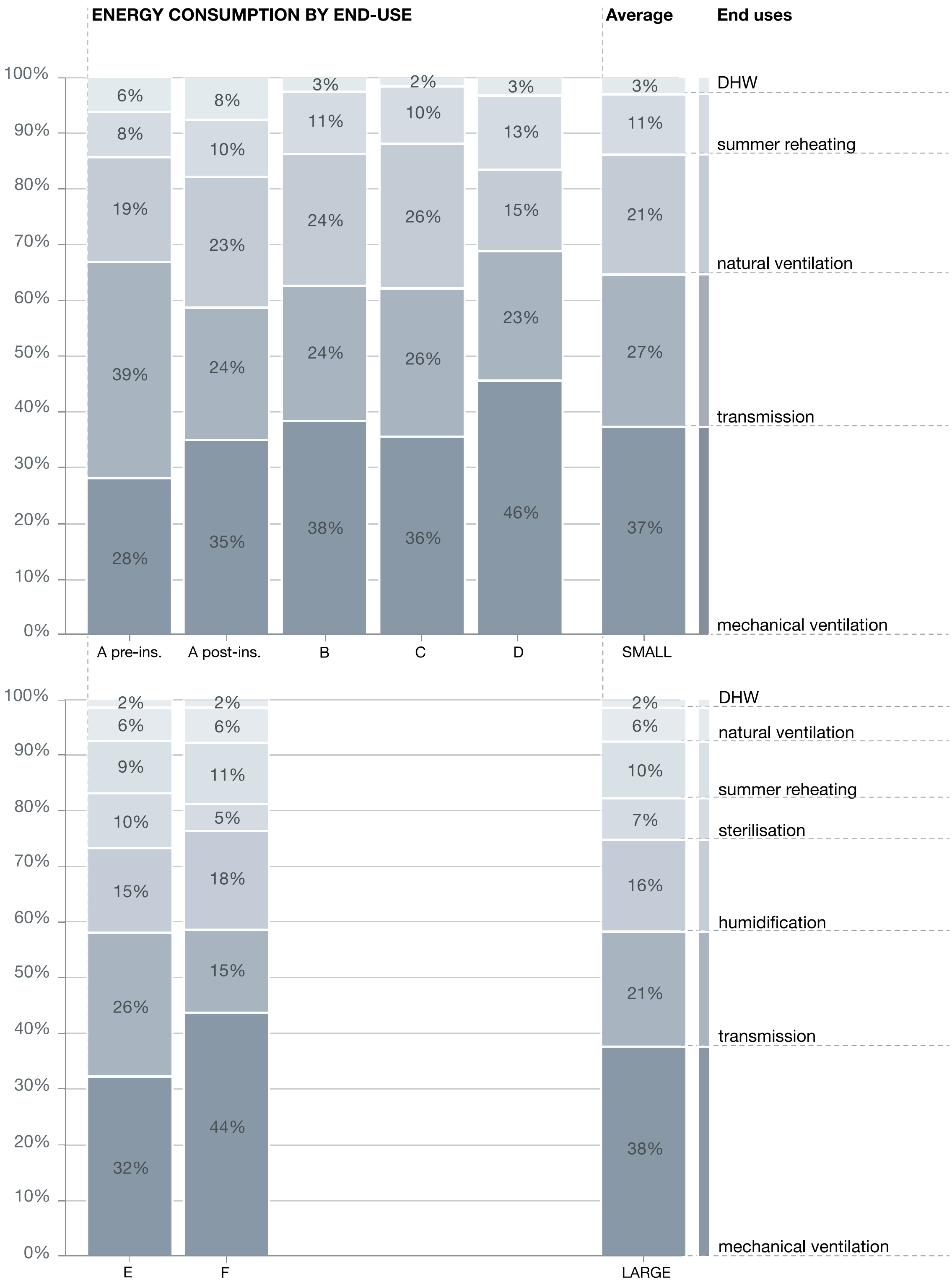


Figure 4.3. End-use energy breakdown for the six hospitals analysed and for small and large hospitals

A first examination of the findings showed that, for all the six hospitals investigated, mechanical ventilation is responsible for the highest thermal energy consumption, followed by transmission, and by humidification in hospitals E and F or by natural ventilation in hospitals A, B, C and D. For a deeper understanding of the results regarding energy consumption for natural and mechanical ventilation, it is necessary to recall that hospitals A, B, C and D have only some functional areas mechanically ventilated, while most of the spaces of hospitals E and F are provided with AHUs. Therefore, specific energy consumption for natural ventilation is decisively higher than energy use for mechanical ventilation, especially for hospital B and C, where it is twice and four times energy use for mechanical ventilation respectively.

In order to aid a comprehensive interpretation of the findings regarding energy consumption for transmission, as it depends on the building S/V ratio and the thermal transmittance of the components of the building envelope, S/V ratios and U-values related to the six hospitals considered are reported in Table 4.17.

In light of this data it was found that hospital F is characterised by the lowest energy consumption for transmission owing to the lowest S/V ratio, besides the very low average thermal transmittance. Despite the highest S/V ratios, hospital B and D present the second and third lowest energy consumption for transmission. This is due to their average U-values, which result to be significantly lower than hospital A, C and E. Indeed, these latter hospitals, despite having a S/V ratio lower than hospital B and D, are characterised by the highest energy consumption for transmission, caused by the very high average thermal transmittance. More in detail, owing to the lower average U-value, hospital A presents a lower energy consumption than hospital C. Taking into consideration hospital E, it was found that it has the highest energy consumption for transmission of all the six hospitals analysed. Indeed, although being characterised by the same S/V ratio as hospital A and C, and by the lowest average U-value, its distribution efficiency, equal to 0.76, is certainly lower than the distribution efficiency of hospital A and C, equal to 0.96 (see Table 4.5).

Table 4.17. S/V ratio and average thermal transmittance of the components of the building envelope

	A		B	C	D	E	F
	pre-ins.	**post ins.**					
S/V	0.43	0.43	0.54	0.43	0.56	0.43	0.34
Average total U-value ($W \cdot m^{-2}K^{-1}$)	1.37	0.87	1.13	1.59	1.02	1.33	1.08
Average U-value ($W \cdot m^{-2}K^{-1}$) of:							
- **external wall**	1.79	0.54	1.63	2.03	1.89	1.62	0.99
- **window**	3.40	3.40	3.33	3.45	3.31	3.66	2.94

- **external roof**	1.60	1.60	0.51	1.71	0.06	1.38	0.38
- **ground floor slab**	0.33	0.33	0.40	0.36	0.31	0.59	0.87

Considering thermal energy consumption for natural and mechanical ventilation, the analysis of the equations used to calculate it (eqs. 5 and 7 outlined in section 4.2.1), shows that it depends on the base of the average air change rate per hour (ACH). For this reason, average air change rates per hour for natural and mechanical ventilation ($ACH_{Nve}{}^{*}$ and $ACH_{Mve}{}^{*}$) assessed at building level are reported below (Table 4.18). The evaluation method and the equations used to calculate the rates are illustrated in section 5.1.2, where are outlined the average air change rates per hour for natural and mechanical ventilation in relation to functional areas (Table 5.3 and 5.4).

Table 4.18. Average air change rates per hour for natural and mechanical ventilation

	A	**B**	**C**	**D**	**E**	**F**
$ACH_{Nve}{}^{*}$ **(1·h-1)**	0.6	1.2	1.5	0.7	0.3	0.3
$ACH_{Mve}{}^{*}$ **(1·h-1)**	0.9	1.9	2.1	2.1	1.6	2.1

Against this background, it was found that hospital C has the highest energy consumption for natural ventilation due to its average air change rate per hour, which results to be the highest of all the six hospitals analysed. The second highest energy consumption for natural ventilation is presented by hospital B, which is indeed characterised by the second highest air change rate per hour, followed by hospital A and D. Differently, as most of their spaces are provided with mechanical ventilation owing to their size, hospital E and F have the lowest energy consumption for natural ventilation.

Likewise, being characterised by the highest air change rates per hour for mechanical ventilation, hospital C, D and F present the highest values of energy consumption. Considering hospital E, although the lower air change rate per hour than hospital D, the facility has a higher energy consumption for mechanical ventilation owing to its distribution efficiency, which is equal to 0.76 and is the lowest of all the six hospitals analysed. Conversely, in spite of the higher air change rate per hour for mechanical ventilation, hospital B is characterised by a lower energy consumption than hospital E. Once again, this is due to the certainly higher distribution efficiency, equal to 0.96. The lowest energy consumption for natural ventilation is presented by hospital A, which has indeed the lowest air change rate per hour.

Taking into account energy consumption for humidification, it is necessary to underline that, for hospital A, B, C and D, thermal energy consumption by end use does not include humidification as this is provided electrically.

4.3.3 End-use energy breakdown in relation to the use of the spaces

The final phase of the energy analysis focused on the investigation of the energy consumed for each end use in relation to functional areas. Results are reported in the following tables and figures, while their interpretation and discussion are illustrated in section 6 in light of the findings outlined in section 5.

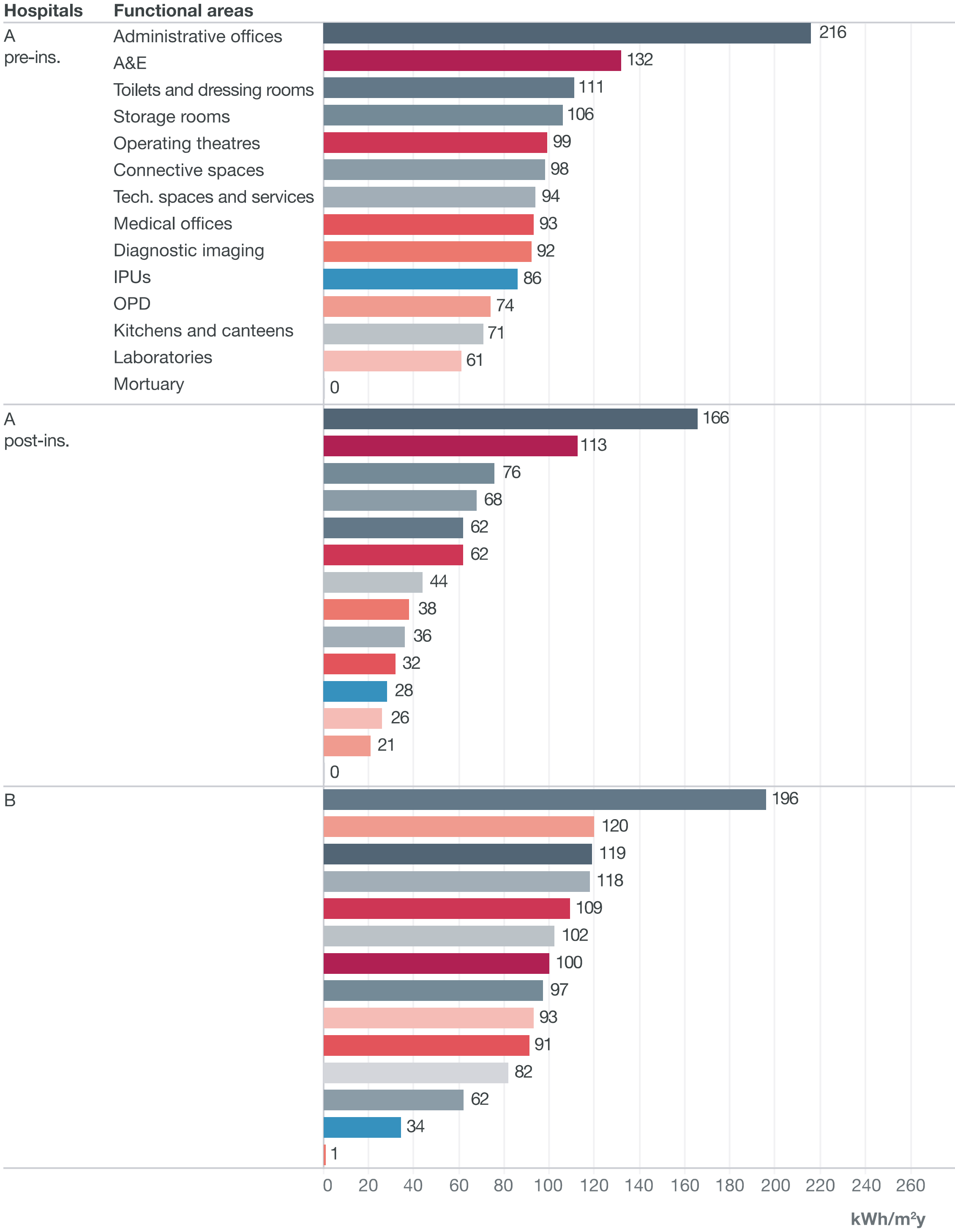
Table 4.19. Energy consumption for transmission by functional area

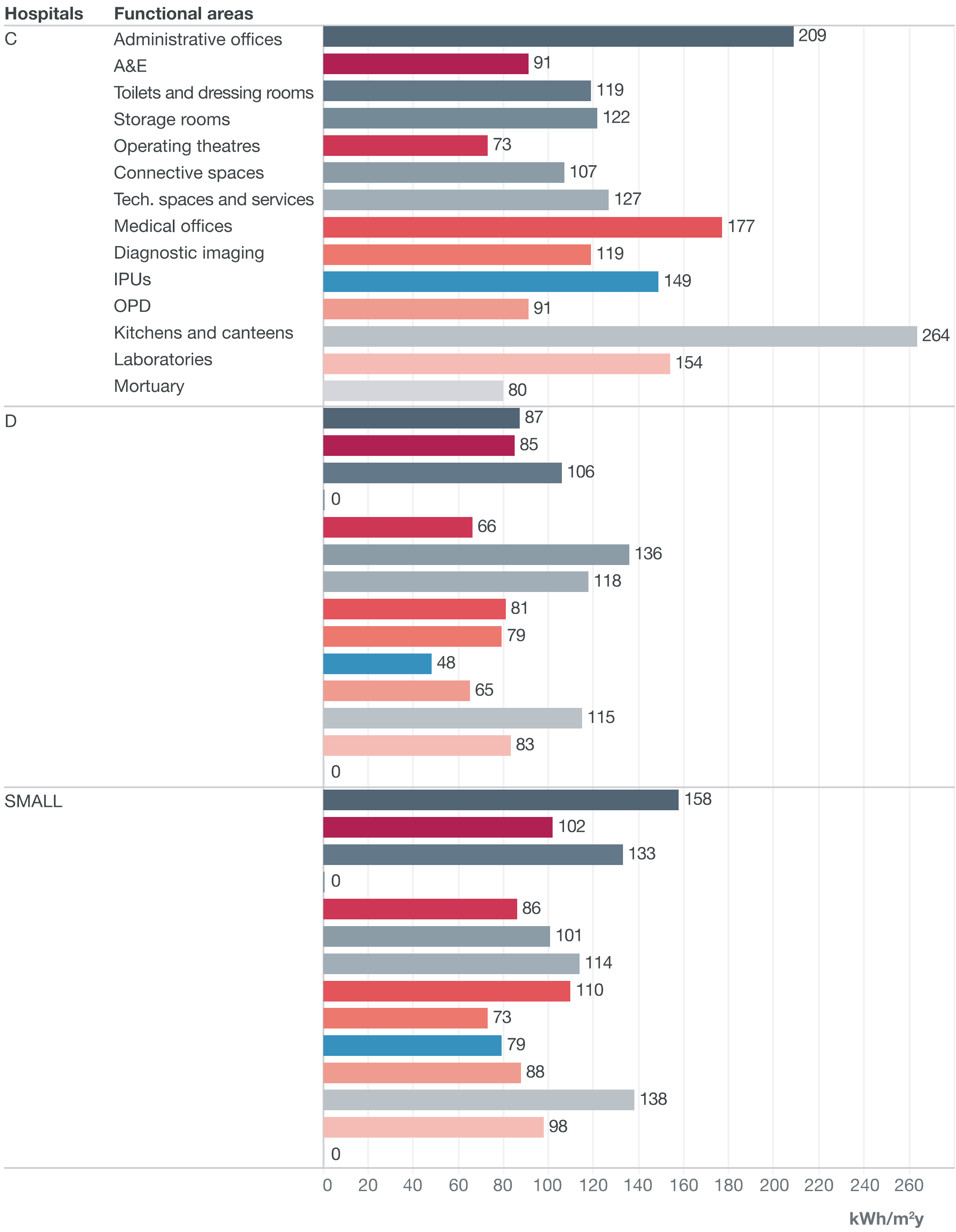
Functional area	Energy consumption for transmission (kWh·m^{-2} y^{-1})						
	A		B	C	D	E	F
	pre-ins.	post ins.					
IPUs	86	28	34	149	48	142	62
A&E	132	113	100	91	85	–	72
OPD	74	21	120	91	65	112	57
Diagnostic imaging	92	38	1	119	79	133	48
Laboratories	61	26	93	154	83	124	100
Medical offices	93	32	91	177	81	138	74
Operating theatres	99	62	109	73	66	174	68
Administrative offices	216	166	119	209	87	193	132
Connective spaces	98	68	62	107	136	112	50
Kitchens and canteens	71	44	102	264	115	193	119
Mortuary	–	–	82	80	–	41	46
Storage rooms	106	76	97	122	–	156	110
Technical spaces and services	94	36	118	127	118	120	57
Toilets and dressing rooms	111	62	196	119	106	185	125
Macro-Area							
IPUs	86	28	34	149	48	142	62
D&T	88	42	93	112	72	129	69
General services	104	67	95	135	120	141	78
Total average	93	45	78	132	77	138	70

Table 4.20. Average energy consumption for transmission in small and large hospitals

Functional area	Energy consumption for transmission (kWh·m^{-2} y^{-1})	
	Small Hospital	Large Hospital
IPUs	79	102
A&E	102	–
OPD	88	85
Diagnostic imaging	73	91
Laboratories	98	112
Medical offices	110	106
Operating theatres	86	121
Administrative offices	158	163
Connective spaces	101	81
Kitchens and canteens	138	156
Mortuary	–	44
Storage rooms	–	133
Technical spaces and services	114	89
Toilets and dressing rooms	133	155
Macro-Area		
IPUs	79	102
D&T	92	99
General services	113	110
Total average	95	104

THERMAL ENERGY USE INTENSITY FOR TRANSMISSION




Hospitals
Functional areas
C
Administrative offices
A&E
Toilets and dressing rooms
Storage rooms
Operating theatres
Connective spaces
Tech. spaces and services
Medical offices
Diagnostic imaging
IPUs
OPD
Kitchens and canteens
Laboratories
Mortuary
209
91
119
122
73
107
127
177
119
149
91
264
154
80
D
87
85
106
0
66
136
118
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48
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83
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SMALL
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133
0
86
101
114
110
73
79
88
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20
40
60
80
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120
140
160
180
200
220
240
260
kWh/m²y

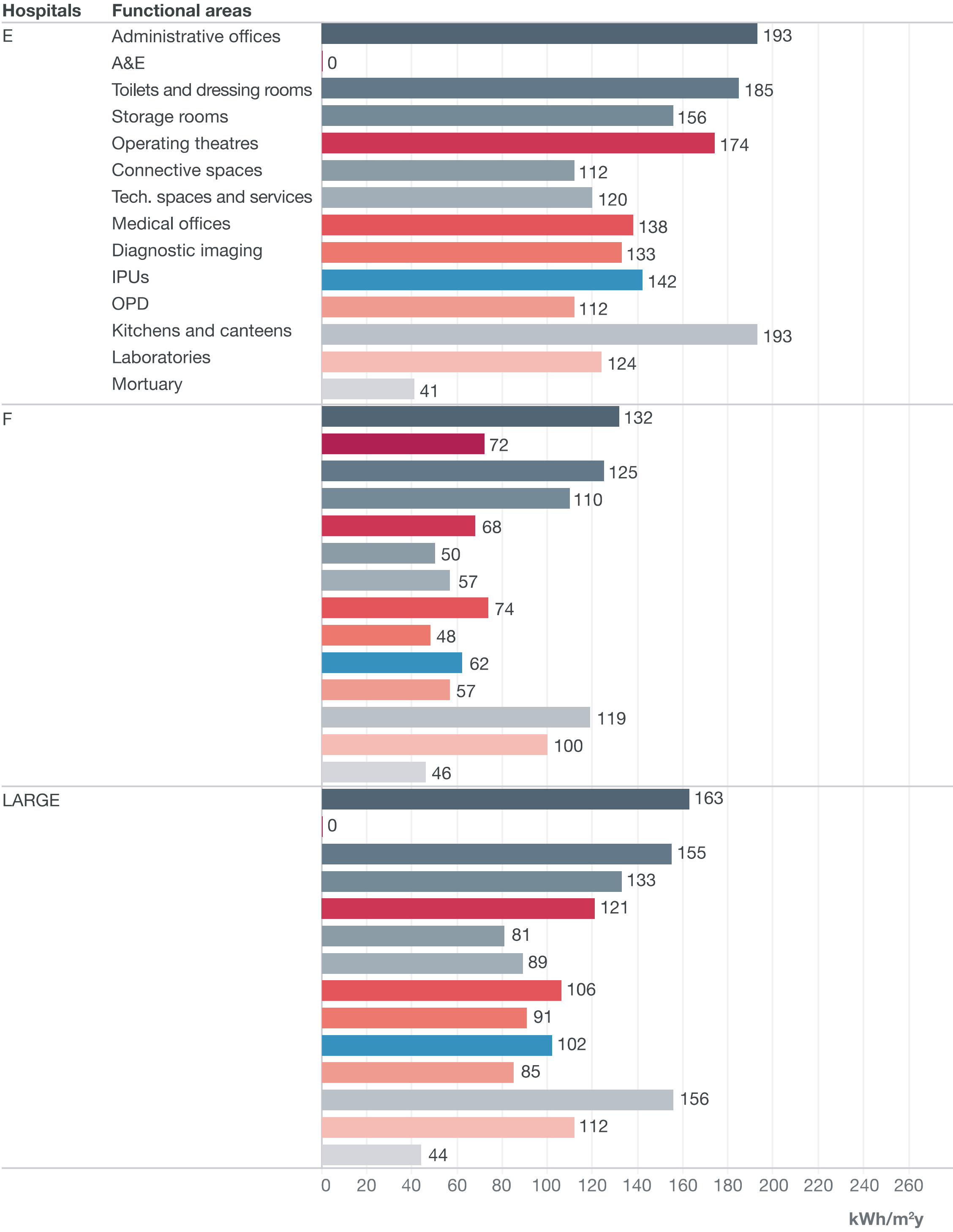


Figure 4.4. Thermal EUI for transmission by functional area

Table 4.21. Percentage distribution of energy consumption for transmission by functional area

Functional area	Energy consumption for transmission (%)						
	A		B	C	D	E	F
	pre-ins.	post ins.					
IPUs	29	19	11	30	21	37	30
A&E	4	6	5	6	3	0	2
OPD	12	7	16	4	15	8	7
Diagnostic imaging	4	4	0	4	3	9	2
Laboratories	1	1	8	3	5	3	6
Medical offices	4	3	6	7	5	5	3
Operating theatres	11	14	7	2	4	3	5
Administrative offices	6	10	9	9	5	6	10
Connective spaces	14	20	12	17	24	11	15
Kitchens and canteens	5	6	6	6	5	4	8
Mortuary	0	0	1	0	0	0	0
Storage rooms	1	2	5	3	0	3	2
Technical spaces and services	4	3	9	5	4	4	3
Toilets and dressing rooms	5	5	5	5	5	5	6
Macro-Area							
IPUs	29	19	11	30	21	37	30
D&T	36	34	43	26	36	29	25
General services	36	47	46	44	43	34	45

Table 4.22. Percentage distribution of energy consumption for transmission in small and large hospitals

	Energy consumption for transmission (%	
Functional area	Small Hospital	Large Hospital
IPUs	24	34
A&E	5	1
OPD	11	8
Diagnostic imaging	3	5
Laboratories	5	5
Medical offices	6	4
Operating theatres	4	4
Administrative offices	7	8
Connective spaces	18	13
Kitchens and canteens	5	6
Mortuary	0	0
Storage rooms	2	3
Technical spaces and services	5	4
Toilets and dressing rooms	5	6
Macro-Area		
IPUs	24	34
D&T	33	27
General services	43	39

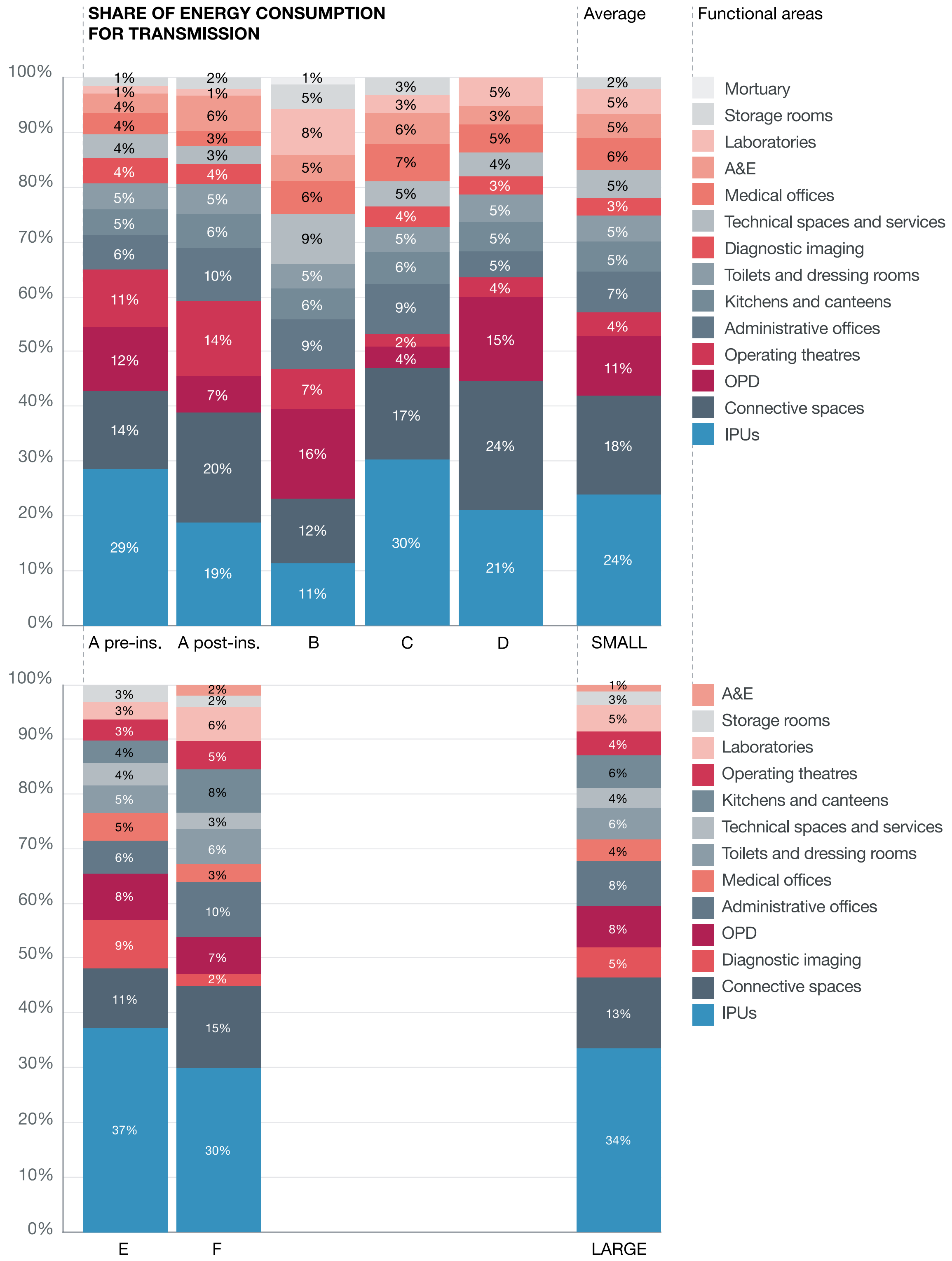


Figure 4.5. Share of energy consumption for transmission by functional area

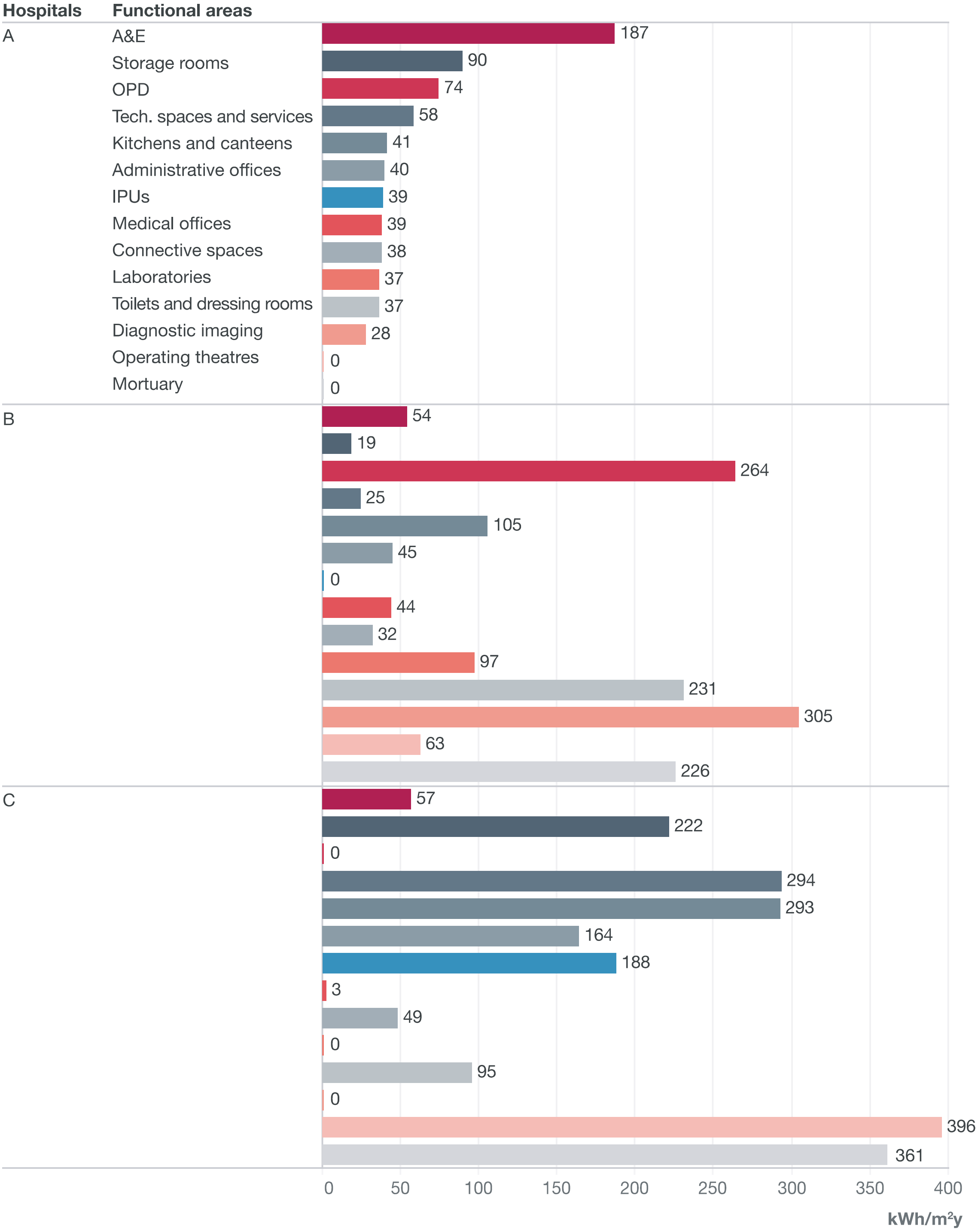
Table 4.23. Energy consumption for natural ventilation by functional area

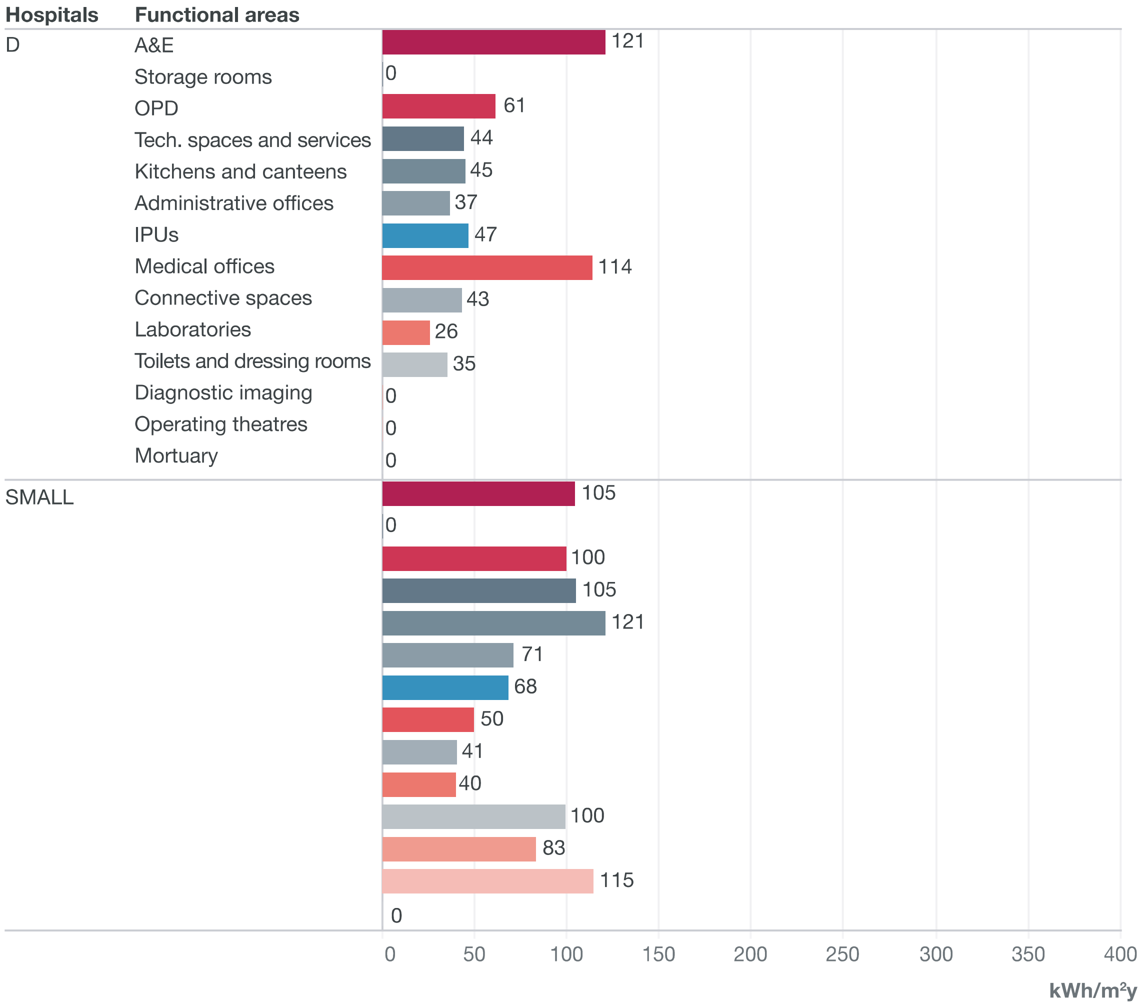
	Energy consumption for natural ventilation (kWh·m^{-2} y^{-1})					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	39	0	188	47	31	30
A&E	187	54	57	121	–	31
OPD	74	264	0	61	30	28
Diagnostic imaging	28	305	0	0	30	30
Laboratories	37	97	0	26	32	30
Medical offices	38	44	3	114	32	30
Operating theatres	0	63	396	0	37	30
Administrative offices	40	45	164	37	36	31
Connective spaces	38	32	49	43	31	30
Kitchens and canteens	41	105	292	45	38	29
Mortuary	–	226	361	–	28	33
Storage rooms	90	19	222	–	30	29
Technical spaces and services	58	25	294	44	30	32
Toilets and dressing rooms	37	231	95	35	30	30
Macro-Area						
IPUs	39	0	188	47	31	30
D&T	51	153	71	56	31	30
General services	43	56	134	42	32	30
Total average	45	76	129	49	31	30

Table 4.24. Average energy consumption for natural ventilation in small and large hospitals

	Energy consumption for natural ventilation (kWh·m^{-2} y^{-1})	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	68	31
A&E	105	–
OPD	100	29
Diagnostic imaging	83	30
Laboratories	40	31
Medical offices	50	31
Operating theatres	115	34
Administrative offices	71	33
Connective spaces	40	31
Kitchens and canteens	121	33
Mortuary	–	30
Storage rooms	–	29
Technical spaces and services	105	31
Toilets and dressing rooms	99	30
Macro-Area		
IPUs	68	31
D&T	83	30
General services	69	31
Total average	75	31

THERMAL ENERGY USE INTENSITY FOR NATURAL VENTILATION





Hospitals
Functional areas
D
A&E
Storage rooms
OPD
Tech. spaces and services
Kitchens and canteens
Administrative offices
IPUs
Medical offices
Connective spaces
Laboratories
Toilets and dressing rooms
Diagnostic imaging
Operating theatres
Mortuary
121
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61
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114
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26
35
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SMALL
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100
105
121
71
68
50
41
40
100
83
115
0
0
50
100
150
200
250
300
350
400
kWh/m²y

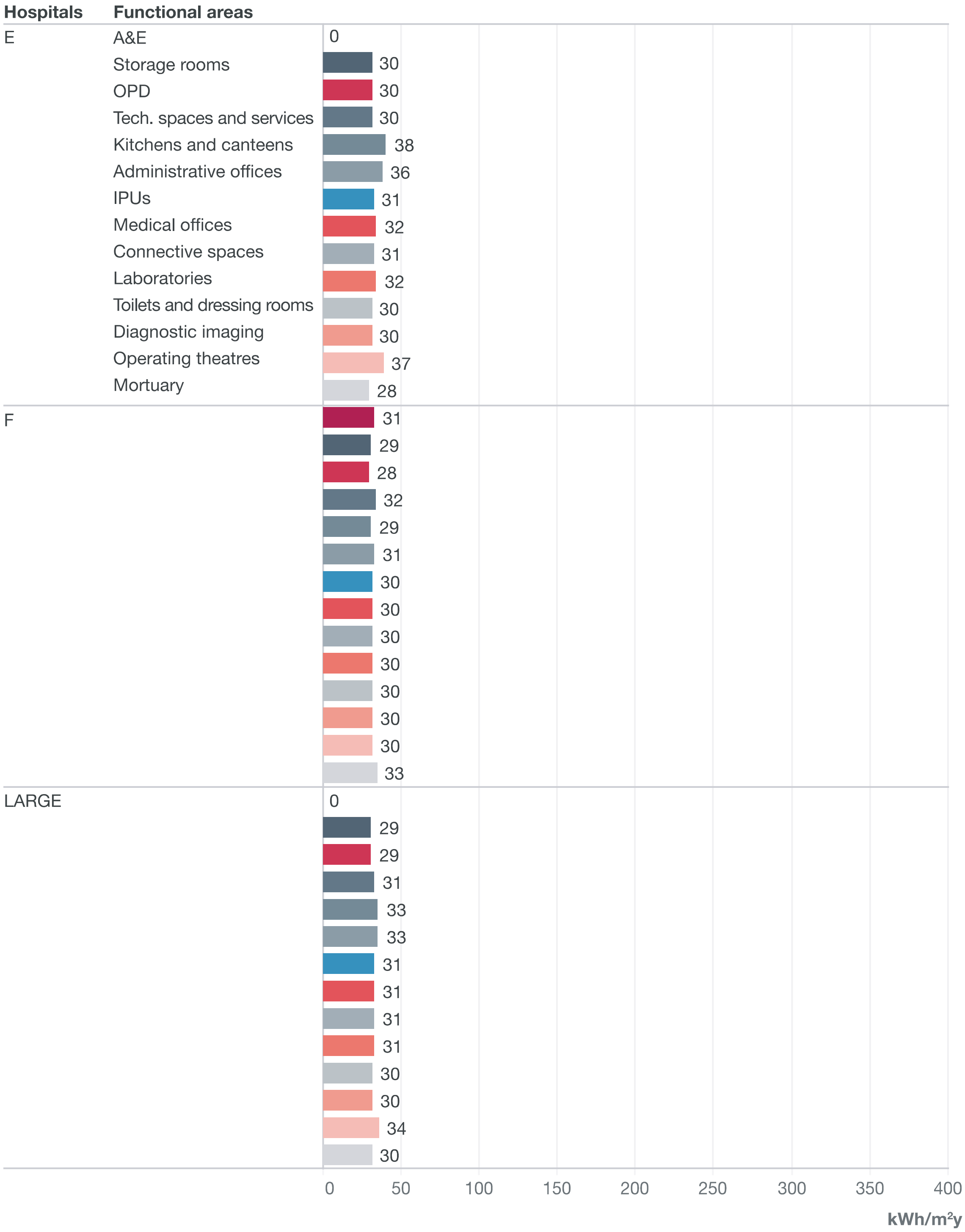


Figure 4.6. Thermal EUI for natural ventilation by functional area

Table 4.25. Percentage distribution of energy consumption for natural ventilation by functional area

	Energy consumption for natural ventilation (%)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	27	0	39	32	36	34
A&E	11	3	4	7	0	2
OPD	24	37	0	23	10	8
Diagnostic imaging	3	16	0	0	9	3
Laboratories	2	9	0	3	4	4
Medical offices	3	3	0	12	5	3
Operating theatres	0	4	13	0	3	5
Administrative offices	2	4	7	3	5	6
Connective spaces	11	6	8	12	13	21
Kitchens and canteens	6	6	7	3	4	5
Mortuary	0	4	2	0	1	1
Storage rooms	2	1	6	0	2	1
Technical spaces and services	6	2	11	3	5	4
Toilets and dressing rooms	3	6	4	3	4	4
Macro-Area						
IPUs	27	0	39	32	36	34
D&T	43	72	17	44	30	25
General services	31	28	44	24	33	41

Table 4.26. Percentage distribution of energy consumption for natural ventilation in small and large hospitals

	Energy consumption for natural ventilation (%)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	29	35
A&E	5	1
OPD	15	9
Diagnostic imaging	3	5
Laboratories	3	4
Medical offices	4	4
Operating theatres	7	5
Administrative offices	5	5
Connective spaces	9	18
Kitchens and canteens	5	4
Mortuary	2	1
Storage rooms	3	2
Technical spaces and services	6	4
Toilets and dressing rooms	4	4
Macro-Area		
IPUs	29	35
D&T	37	27
General services	34	38

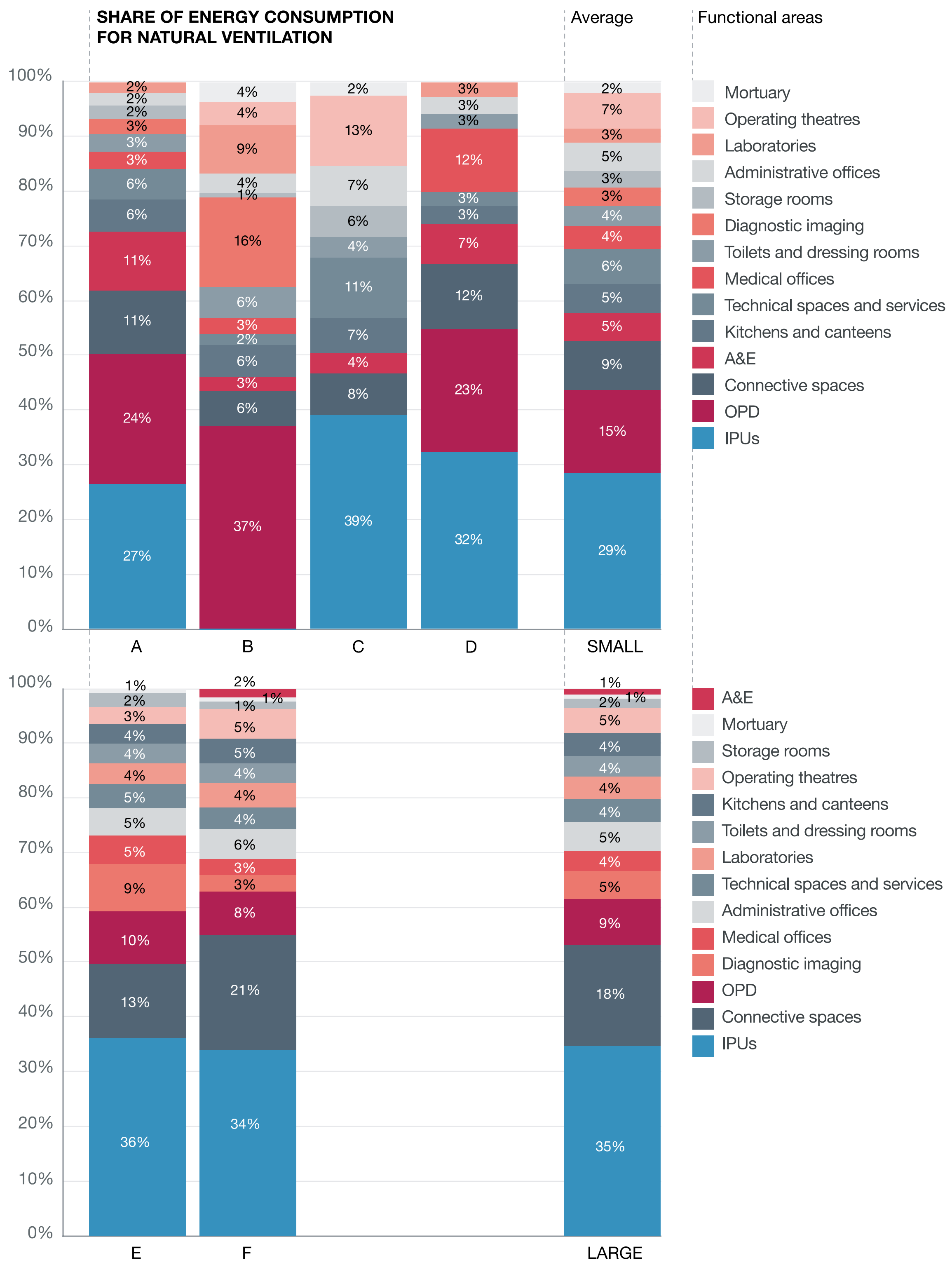


Figure 4.7. Share of energy consumption for natural ventilation by functional area

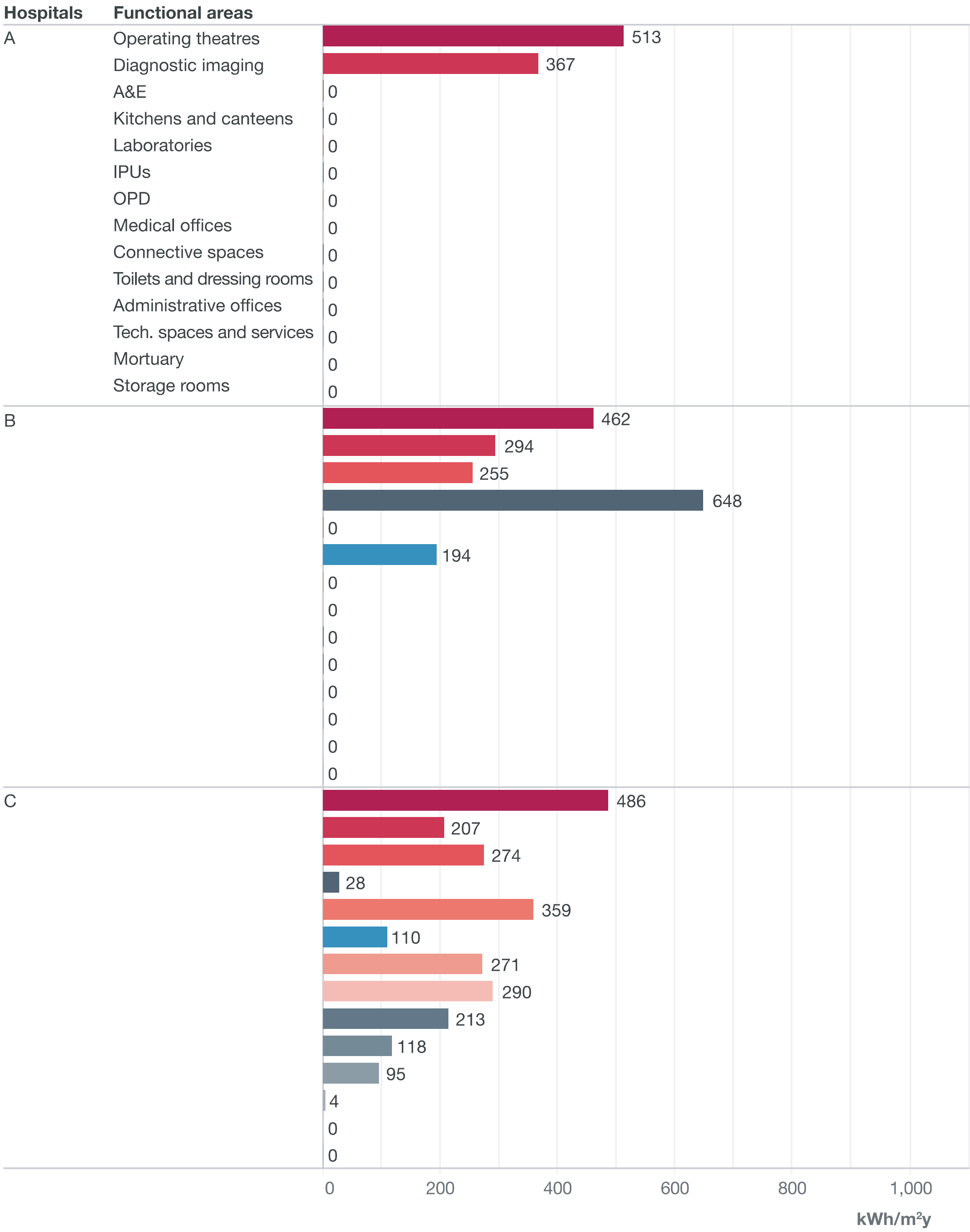
Table 4.27. Energy consumption for mechanical ventilation by functional area

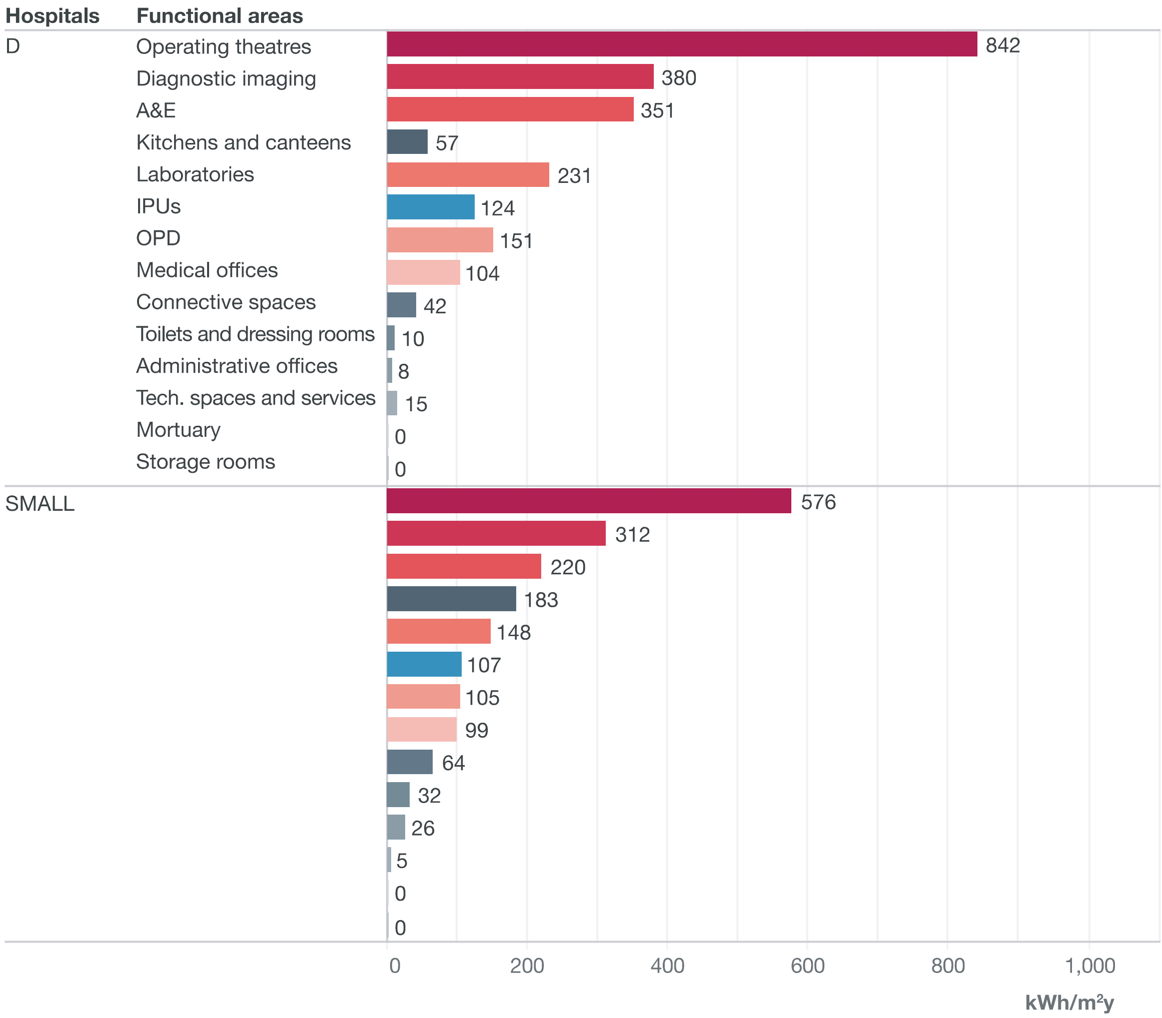
	Energy consumption for mechanical ventilation ($kWh \cdot m^{-2} y^{-1}$)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	0	194	110	124	148	151
A&E	0	255	274	351	–	125
OPD	0	0	271	151	296	214
Diagnostic imaging	367	294	207	380	215	342
Laboratories	0	0	359	231	278	575
Medical offices	0	0	290	104	174	132
Operating theatres	513	462	486	842	728	1,042
Administrative offices	0	0	95	8	191	103
Connective spaces	0	0	213	42	0	1
Kitchens and canteens	0	648	28	57	0	0
Mortuary	–	0	0	–	476	174
Storage rooms	0	0	0	–	0	0
Technical spaces and services	0	0	4	15	255	562
Toilets and dressing rooms	0	0	118	10	112	365
Macro-Area						
IPUs	0	194	110	124	148	151
D&T	180	127	304	265	289	449
General services	0	73	130	32	89	102
Total average	67	124	177	153	172	208

Table 4.28. Average energy consumption for mechanical ventilation in small and large hospitals

	Energy consumption for mechanical ventilation ($kWh \cdot m^{-2} y^{-1}$)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	107	150
A&E	220	–
OPD	105	255
Diagnostic imaging	312	278
Laboratories	148	426
Medical offices	99	153
Operating theatres	576	885
Administrative offices	26	147
Connective spaces	64	1
Kitchens and canteens	183	0
Mortuary	–	325
Storage rooms	–	0
Technical spaces and services	5	409
Toilets and dressing rooms	32	238
Macro-Area		
IPUs	107	150
D&T	219	369
General services	59	95
Total average	130	190

THERMAL ENERGY USE INTENSITY FOR MECHANICAL VENTILATION





Hospitals
Functional areas
D
Operating theatres
Diagnostic imaging
A&E
Kitchens and canteens
Laboratories
IPUs
OPD
Medical offices
Connective spaces
Toilets and dressing rooms
Administrative offices
Tech. spaces and services
Mortuary
Storage rooms
842
380
351
57
231
124
151
104
42
10
8
15
0
0
SMALL
576
312
220
183
148
107
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99
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32
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200
400
600
800
1,000
kWh/m²y

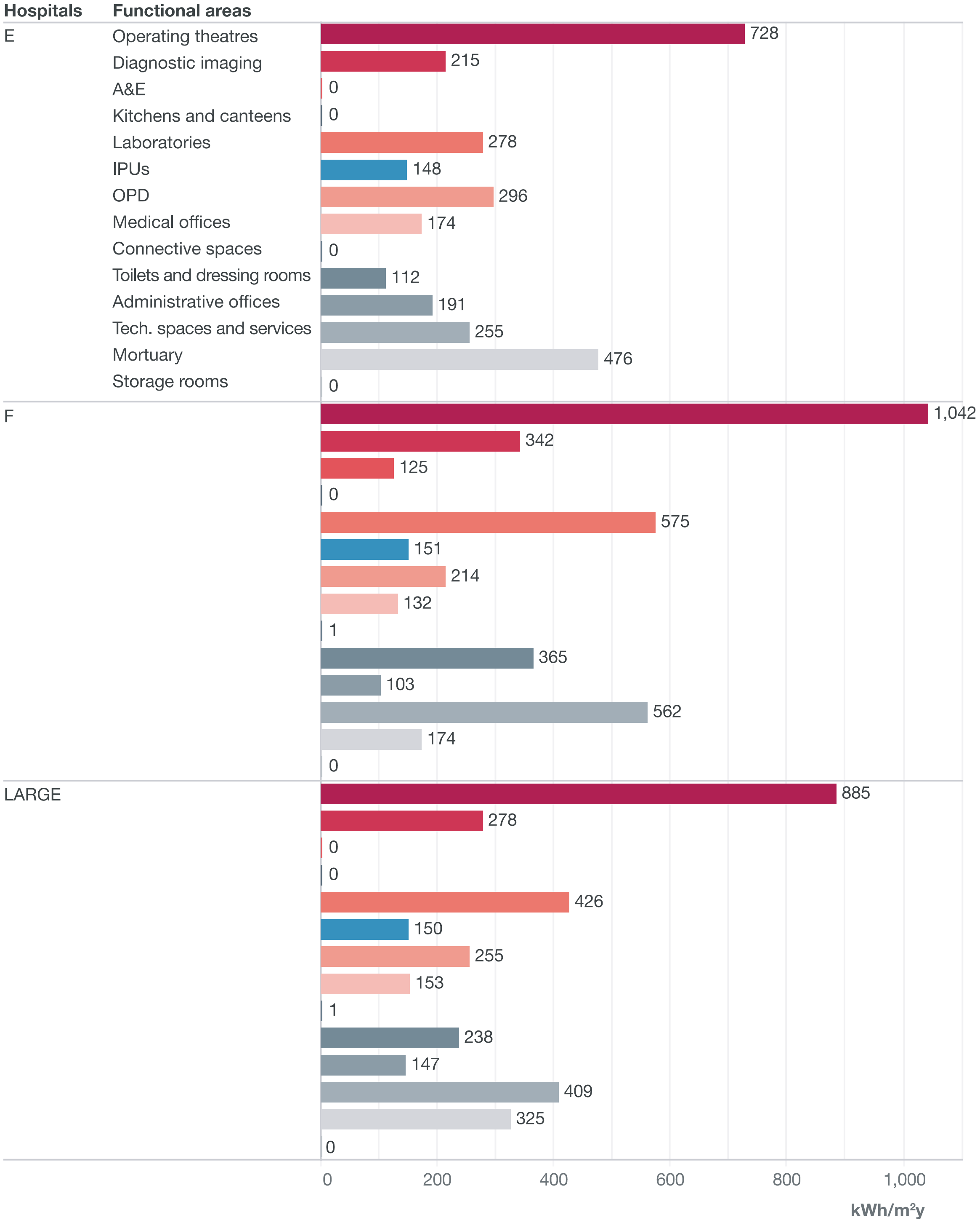

Figure 4.8. Thermal EUI for mechanical ventilation by functional area

Table 4.29. Percentage distribution of energy consumption for mechanical ventilation by functional area

	Energy consumption for mechanical ventilation (%)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	0	41	17	27	31	25
A&E	0	8	13	7	0	1
OPD	0	0	9	18	18	9
Diagnostic imaging	24	10	5	8	11	5
Laboratories	0	0	6	7	6	12
Medical offices	0	0	8	3	5	2
Operating theatres	76	19	11	23	12	27
Administrative offices	0	0	3	0	5	3
Connective spaces	0	0	25	4	0	0
Kitchens and canteens	0	22	0	1	0	0
Mortuary	0	0	0	0	3	0
Storage rooms	0	0	0	0	0	0
Technical spaces and services	0	0	0	0	7	10
Toilets and dressing rooms	0	0	3	0	2	6
Macro-Area						
IPUs	0	41	17	27	31	25
D&T	100	37	52	67	52	55
General services	0	22	32	6	17	20

Table 4.30. Percentage distribution of energy consumption for mechanical ventilation in small and large hospitals

	Energy consumption for mechanical ventilation (%)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	25	27
A&E	9	1
OPD	11	11
Diagnostic imaging	8	7
Laboratories	5	10
Medical offices	4	3
Operating theatres	21	22
Administrative offices	1	3
Connective spaces	10	0
Kitchens and canteens	5	0
Mortuary	0	1
Storage rooms	0	0
Technical spaces and services	0	9
Toilets and dressing rooms	1	5
Macro-Area		
IPUs	25	27
D&T	59	54
General services	17	19

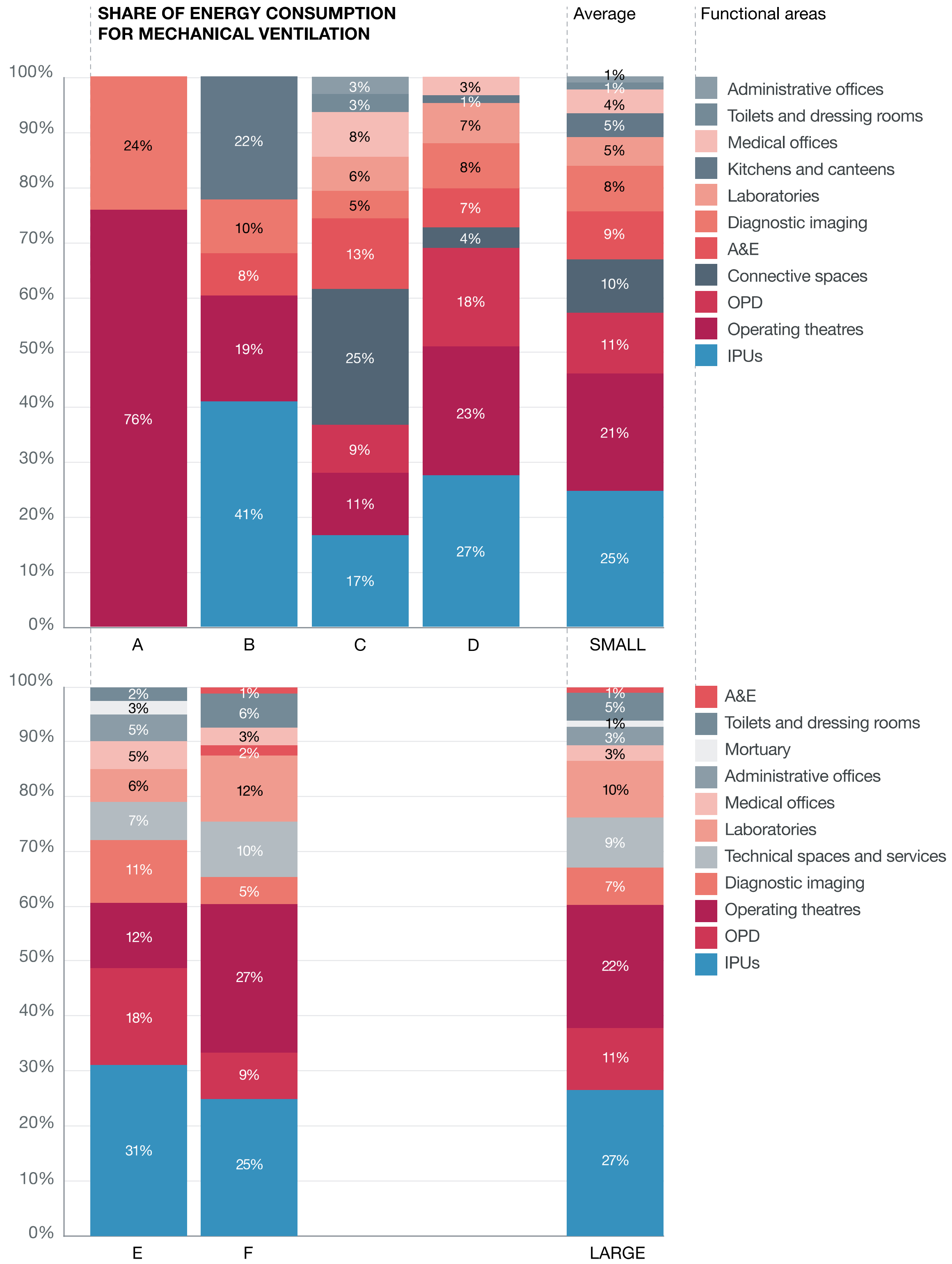

Figure 4.9. Share of energy consumption for mechanical ventilation by functional area

Table 4.31. Energy consumption for humidification by functional area

	Energy consumption for humidification ($kWh \cdot m^{-2} y^{-1}$)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	–	–	–	–	70	61
A&E	–	–	–	–	–	51
OPD	–	–	–	–	140	87
Diagnostic imaging	–	–	–	–	102	139
Laboratories	–	–	–	–	131	233
Medical offices	–	–	–	–	82	53
Operating theatres	–	–	–	–	344	422
Administrative offices	–	–	–	–	90	42
Connective spaces	–	–	–	–	0	0
Kitchens and canteens	–	–	–	–	0	0
Mortuary	–	–	–	–	225	71
Storage rooms	–	–	–	–	0	0
Technical spaces and services	–	–	–	–	121	228
Toilets and dressing rooms	–	–	–	–	53	148
Macro-Area						
IPUs	–	–	–	–	70	61
D&T	–	–	–	–	136	182
General services	–	–	–	–	42	41
Total average	–	–	–	–	81	84

Table 4.32. Average energy consumption for humidification in large hospitals

	Energy consumption for humidification ($kWh \cdot m^{-2} y^{-1}$)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	–	66
A&E	–	–
OPD	–	113
Diagnostic imaging	–	120
Laboratories	–	182
Medical offices	–	68
Operating theatres	–	383
Administrative offices	–	66
Connective spaces	–	0
Kitchens and canteens	–	0
Mortuary	–	148
Storage rooms	–	0
Technical spaces and services	–	174
Toilets and dressing rooms	–	100
Macro-Area		
IPUs	–	66
D&T	–	159
General services	–	42
Total average	–	83

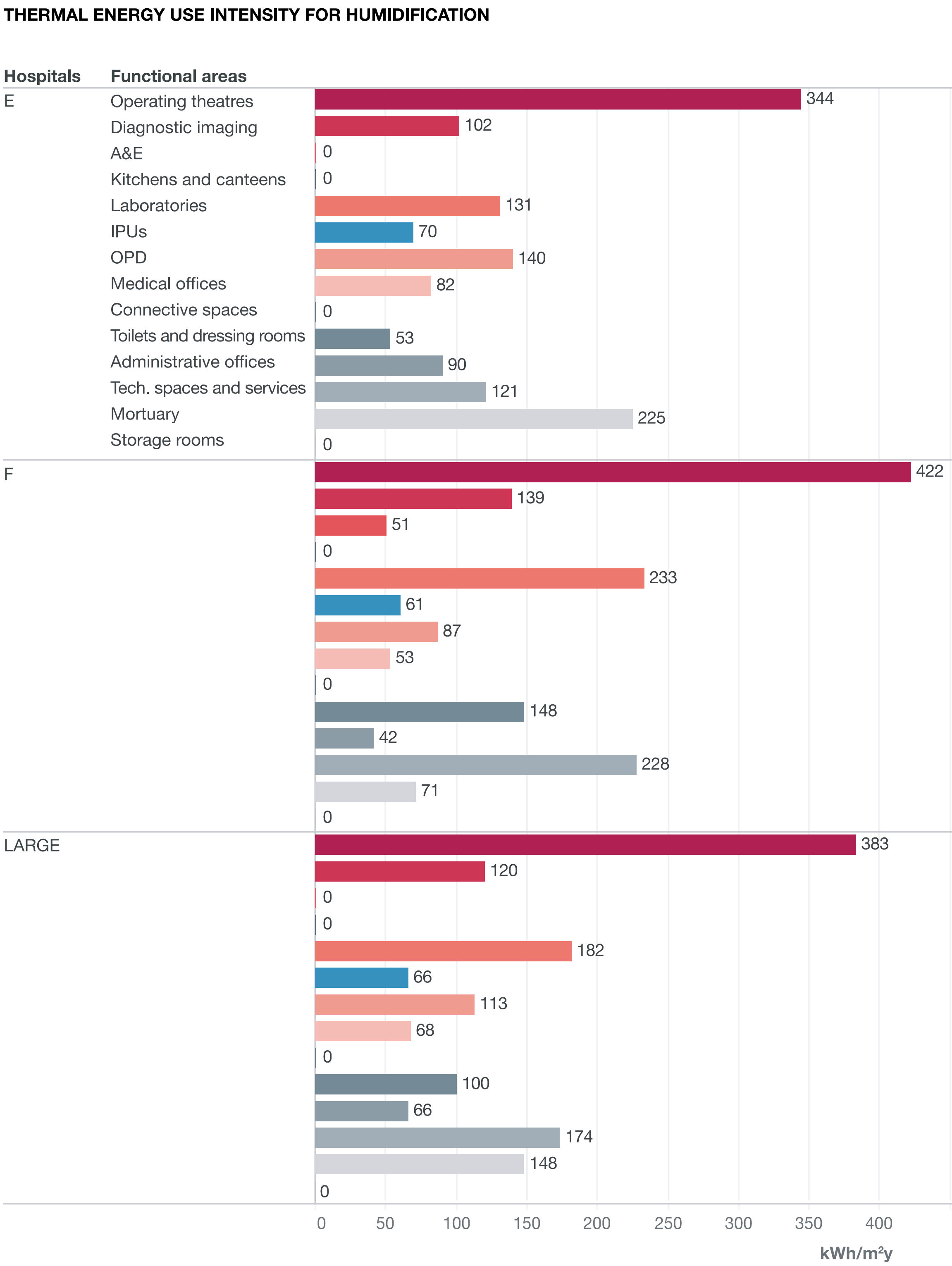

Figure 4.10. Thermal EUI for humidification by functional area

Table 4.33. Percentage distribution of energy consumption for humidification by functional area

	Energy consumption for humidification (%)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	–	–	–	–	31	25
A&E	–	–	–	–	0	1
OPD	–	–	–	–	18	9
Diagnostic imaging	–	–	–	–	11	5
Laboratories	–	–	–	–	6	12
Medical offices	–	–	–	–	5	2
Operating theatres	–	–	–	–	12	27
Administrative offices	–	–	–	–	5	3
Connective spaces	–	–	–	–	0	0
Kitchens and canteens	–	–	–	–	0	0
Mortuary	–	–	–	–	3	0
Storage rooms	–	–	–	–	0	0
Technical spaces and services	–	–	–	–	7	10
Toilets and dressing rooms	–	–	–	–	2	6
Macro-Area						
IPUs	–	–	–	–	31	25
D&T	–	–	–	–	52	55
General services	–	–	–	–	17	20

Table 4.34. Percentage distribution of energy consumption for humidification in large hospitals

	Energy consumption for humidification (%)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	–	27
A&E	–	1
OPD	–	11
Diagnostic imaging	–	7
Laboratories	–	10
Medical offices	–	3
Operating theatres	–	22
Administrative offices	–	3
Connective spaces	–	0
Kitchens and canteens	–	0
Mortuary	–	1
Storage rooms	–	0
Technical spaces and services	–	9
Toilets and dressing rooms	–	5
Macro-Area		
IPUs	–	27
D&T	–	54
General services	–	19

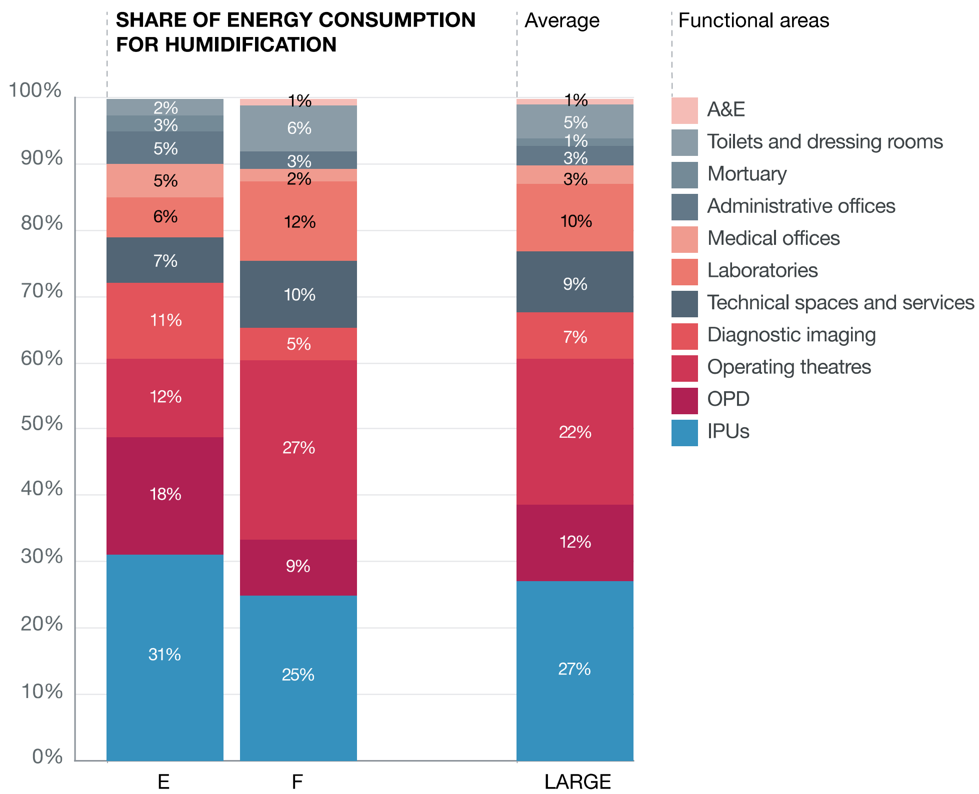

Figure 4.11. Share of energy consumption for humidification by functional area

Table 4.35. Energy consumption for summer reheating by functional area

	Energy consumption for summer reheating (kWh·m-2 y-1)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	0	0	0	0	10	15
A&E	0	0	53	264	–	279
OPD	0	0	30	1	12	40
Diagnostic imaging	0	0	0	0	14	9
Laboratories	0	0	449	34	0	1
Medical offices	0	155	5	12	0	0
Operating theatres	0	287	206	291	563	241
Administrative offices	0	0	0	0	0	0
Connective spaces	0	0	14	24	22	30
Kitchens and canteens	0	65	233	86	0	11
Mortuary	–	287	453	–	616	432
Storage rooms	1230	188	176	–	225	1047
Technical spaces and services	0	0	88	55	53	26
Toilets and dressing rooms	0	0	32	3	65	38
Macro-Area						
IPUs	0	0	0	0	10	15
D&T	0	64	91	58	87	82
General services	61	35	56	79	60	64
Total average	20	36	52	44	50	52

Table 4.36. Average energy consumption for summer reheating in small and large hospitals

	Energy consumption for summer reheating ($kWh \cdot m^{-2} y^{-1}$)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	0	13
A&E	79	–
OPD	8	26
Diagnostic imaging	0	11
Laboratories	121	1
Medical offices	43	0
Operating theatres	196	402
Administrative offices	0	0
Connective spaces	10	26
Kitchens and canteens	96	5
Mortuary	–	524
Storage rooms	–	636
Technical spaces and services	36	40
Toilets and dressing rooms	9	51
Macro-Area		
IPUs	0	13
D&T	54	85
General services	58	62
Total average	38	51

Results regarding thermal energy consumption for the six hospitals considered, here reported in kWh, are expressed in Nm^3 in Appendix C.

5 Development of the energy consumption analysis and forecasting model

The data collected and the results obtained for the six hospitals analysed allowed to develop a data-driven model for building energy analysis and forecasting.

The definition of the model, which enables to evaluate and predict energy consumption for transmission, natural ventilation, mechanical ventilation and humidification, was based on the identification of the main variables affecting this end-uses.

5.1 Definition of the model variables

5.1.1 Average thermal transmittance

Theoretical building energy demand for transmission $\dot{Q}_{tr\,TH}$ is calculated with the following equation:

$$\dot{Q}_{tr\,TH} = \sum \mu_i \left[\frac{W}{m^2\ °C}\right]\ S_i\ [m^2]\ \Delta T\ [°C] \qquad [W] \qquad (17)$$

where μ_i is the thermal transmittance of the considered portion of building envelope element, S_i is the related external surface and ΔT is the difference between winter indoor and outdoor design temperature, equal to 25°C (see Table 4.2).

Therefore, we can define the parameter μ^* as the variable describing the average value of thermal transmittance for the whole building envelope, evaluated as:

$$\mu^* = \frac{\dot{Q}_{tr\,TH}[W]}{S_{tot}[m^2]\ \Delta T[°C]} \qquad \left[\frac{W}{m^2\ °C}\right] \tag{18}$$

where S_{tot} is the total external surface of the building.

Results regarding the average thermal transmittance assessed for the six hospitals considered are reported in the following table (Table 5.1).

Table 5.1. Average thermal transmittance in relation to the use of the spaces

	Average thermal transmittance μ^* (W·m-2 C-1)						
Functional area	**A**		**B**	**C**	**D**	**E**	**F**
	pre-ins.	**post ins.**					
IPUs	1.8	0.9	1.2	2.1	1.0	1.5	1.5
A&E	1.1	1.0	1.2	2.6	1.0	–	1.1
OPD	1.5	0.8	1.2	1.1	0.9	1.2	1.1
Diagnostic imaging	1.0	0.6	0.5	1.3	0.9	1.4	1.0
Laboratories	1.0	0.7	1.2	1.6	1.1	1.3	1.0
Medical offices	1.6	0.9	1.4	1.5	1.1	1.2	0.9
Operating theatres	1.1	0.8	1.2	1.0	1.3	1.4	0.9
Administrative offices	2.1	1.7	1.2	1.6	0.9	1.4	1.1
Connective spaces	1.4	1.1	1.0	1.4	1.1	1.2	0.9
Kitchens and canteens	0.8	0.6	1.0	2.0	1.0	1.4	0.8
Mortuary	–	–	0.8	0.9	–	1.1	1.2
Storage rooms	1.1	0.9	1.2	1.1	–	1.1	1.0
Technical spaces and services	1.5	0.8	1.2	1.6	1.3	1.1	1.1
Toilets and dressing rooms	1.0	0.7	1.4	1.2	1.0	1.1	0.9
Macro-Area							
IPUs	1.8	0.9	1.2	2.1	1.0	1.5	1.5
D&T	1.3	0.8	1.2	1.4	1.0	1.3	1.0
General services	1.2	0.9	1.1	1.4	1.1	1.2	0.9
Total average	1.37	0.87	1.13	1.59	1.02	1.33	1.08

Table 5.2. Average thermal transmittance in relation to the use of the spaces in small and large hospitals

	Average thermal transmittance μ^* (W·m-2 C-1)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	1.4	1.5
A&E	1.5	0.5
OPD	1.0	1.2

Diagnostic imaging	1.0	1.3
Laboratories	1.2	1.1
Medical offices	1.3	1.1
Operating theatres	1.2	1.1
Administrative offices	1.3	1.2
Connective spaces	1.2	1.0
Kitchens and canteens	1.2	1.0
Mortuary	0.4	1.1
Storage rooms	0.8	1.1
Technical spaces and services	1.4	1.1
Toilets and dressing rooms	1.1	1.0
Macro-Area		
IPUs	1.4	1.5
D&T	1.2	1.1
General services	1.2	1.0
Total average	1.2	1.2

Theoretical energy demand for transmission calculated for the six hospitals analysed in relation to the functional areas, and used to assess the average thermal transmittance, are outlined in Appendix B, table B.1.

5.1.2 Average air change rate per hour

Theoretical energy demand for ventilation $\dot{Q}_{ve\,TH}$ includes energy needs for natural ventilation $\dot{Q}_{Nve\,TH}$, mechanical ventilation $\dot{Q}_{Mve\,TH}$ and humidification $\dot{Q}_{HUM\,TH}$ (eq. 19).

$$\dot{Q}_{ve\,TH} = \dot{Q}_{Nve\,TH}[W] + \dot{Q}_{Mve\,TH}\,[W] + \dot{Q}_{HUM\,TH}\,[W] \qquad [W] \qquad (19)$$

Energy needs for natural and mechanical ventilation are calculated on the base of eqs. (20) and (21) respectively, while energy needs for humidification are assessed on the base of eq. (22), as already outlined in section 4.2.1.2, section 4.2.1.3 and in section 4.2.1.4:

$$\dot{Q}_{Nve\,TH} = \sum ACH_{Nve_i}\left[\frac{1}{h}\right]\ V_{Nve_i}[m^3]\ \rho_{air}\left[\frac{kg}{m^3}\right]\ cp_{air}\left[\frac{kJ}{kg°C}\right]\ \Delta T[°C]\ \frac{1}{3600}\left[\frac{kWh}{kJ}\right] \qquad [kW] \qquad (20)$$

$$\dot{Q}_{Mve\,TH} = \sum ACH_{Mve_i}\left[\frac{1}{h}\right]\ V_{Mve_i}[m^3]\ \rho_{air}\left[\frac{kg}{m^3}\right]\ cp_{air}\left[\frac{kJ}{kg°C}\right]\ \Delta T[°C]\ \frac{1}{3600}\left[\frac{kWh}{kJ}\right] \qquad [kW] \qquad (21)$$

$$\dot{Q}_{HUM\ TH} = \sum ACH_{Mve_i}\left[\frac{1}{h}\right]\ V_{Mve_i}[m^3]\ \rho_{air}\left[\frac{kg}{m^3}\right]\frac{\Delta y\left[\frac{g}{kg_{dry\ air}}\right]}{1000}\ r\left[\frac{kcal}{kg}\right]\frac{1}{860}\left[\frac{kWh}{kcal}\right]\quad [kW] \tag{22}$$

where ACH_{Nve_i} and ACH_{Mve_i} are the air change rates per hour for natural or mechanical ventilation of the considered hospital space, V_{Nve_i} and V_{Mve_i} is the relative volume of the space, ρ_{air} is density of air, equal to 1,2 kg·m-3, cp_{air} is the specific heat capacity of air, equal to 1,005 kJ·(kg°C)-1, ΔT is the difference between winter indoor and outdoor design temperature, equal to 25°C.

The analysis of eqs. (20), (21) and (22) underlines that energy consumption for natural ventilation, mechanical ventilation and humidification depends on the air change rate per hour. Therefore, likewise the average thermal transmittance, we can define the variables $ACH_{Nve}{}^{*}$ and $ACH_{Mve}{}^{*}$, which describe the average air change rates per hour for natural and mechanical ventilation respectively, evaluated as:

$$ACH_{Nve}{}^{*} = \frac{\sum ACH_{Nve_i}\left[\frac{1}{h}\right]\ V_{Nve_i}[m^3]}{\sum V_{Nve_i}[m^3]}\qquad\left[\frac{1}{h}\right] \tag{23}$$

$$ACH_{Mve}{}^{*} = \frac{\sum ACH_{Mve_i}\left[\frac{1}{h}\right]\ V_{Mve_i}[m^3]}{\sum V_{Mve_i}[m^3]}\qquad\left[\frac{1}{h}\right] \tag{24}$$

Similarly, the general average air change rate per hour for the whole building can be defined with the following equation:

$$ACH^{*} = \frac{\sum ACH_i\left[\frac{1}{h}\right]\ V_i[m^3]}{\sum V_i\ [m^3]}\qquad\left[\frac{1}{h}\right] \tag{25}$$

The average air change rates per hour for natural ventilation and for mechanical ventilation assessed for the six hospitals considered in relation to the functional areas are reported in Table 5.3 and Table 5.4, while in Table 5.5 is outlined the general average air change rate per hour ACH^{*}.

Table 5.3. Average air change rate per hour for natural ventilation in relation to the use of the space

	Average air change rate per hour for natural ventilation ACH_{Nve}^{*} ($1 \cdot h^{-1}$)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	0.5	0.0	2.0	0.7	0.3	0.3
A&E	2.6	0.8	0.5	1.7	–	0.3
OPD	1.0	4.1	0.0	0.9	0.3	0.3
Diagnostic imaging	0.4	4.7	0.0	0.0	0.3	0.3
Laboratories	0.5	1.5	0.0	0.4	0.3	0.3
Medical offices	0.5	0.7	0.0	1.6	0.3	0.3
Operating theatres	0.0	1.0	4.7	0.0	0.3	0.3
Administrative offices	0.5	0.7	2.2	0.5	0.3	0.3
Connective spaces	0.5	0.5	0.6	0.6	0.3	0.3
Kitchens and canteens	0.6	1.6	2.8	0.6	0.3	0.3
Mortuary	–	3.5	8.7	–	0.3	0.3
Storage rooms	1.2	0.3	3.3	–	0.3	0.3
Technical spaces and services	0.8	0.4	3.5	0.6	0.3	0.3
Toilets and dressing rooms	0.5	3.6	1.3	0.5	0.3	0.3
Macro-Area						
IPUs	0.5	0.0	2.0	0.7	0.3	0.3
D&T	0.7	2.4	0.8	0.8	0.3	0.3
General services	0.6	0.9	1.7	0.6	0.3	0.3
Total average	0.6	1.2	1.5	0.7	0.3	0.3

Table 5.4. Average air change rate per hour for mechanical ventilation in relation to the use of the space

	Average air change rate per hour for mechanical ventilation ACH_{Mve}^{*} ($1 \cdot h^{-1}$)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	0.0	3.0	1.1	1.7	1.4	1.5
A&E	0.0	3.9	2.5	4.9	–	1.2
OPD	0.0	0.0	4.0	2.1	3.0	2.3
Diagnostic imaging	5.1	4.5	3.2	5.3	2.2	3.4
Laboratories	0.0	0.0	5.0	3.2	2.6	5.7
Medical offices	0.0	0.0	3.4	1.5	1.6	1.3
Operating theatres	7.1	7.1	5.8	11.8	5.9	10.3
Administrative offices	0.0	0.0	1.3	0.1	1.6	1.0
Connective spaces	0.0	0.0	2.5	0.6	0.0	0.0
Kitchens and canteens	0.0	10.0	0.3	0.8	0.0	0.0
Mortuary	–	0.0	0.0	–	5.2	1.6
Storage rooms	0.0	0.0	0.0	–	0.0	0.0
Technical spaces and services	0.0	0.0	0.1	0.2	2.6	5.3
Toilets and dressing rooms	0.0	0.0	1.7	0.1	1.1	3.6
Macro-Area						
IPUs	0.0	3.0	1.1	1.7	1.4	1.5
D&T	2.4	2.0	3.6	3.7	2.8	4.5
General services	0.0	1.1	1.6	0.4	0.8	1.0
Total average	0.9	1.9	2.1	2.1	1.6	2.1

Table 5.5. Average air change rate per hour in relation to the use of the space

	Average air change rate per hour $ACH^{*}(1 \cdot h^{-1})$					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	0.5	3.0	3.1	2.4	1.7	1.8
A&E	2.6	4.8	3.0	6.6	–	1.5
OPD	1.0	4.1	4.0	3.0	3.3	2.6
Diagnostic imaging	5.5	9.3	3.2	5.3	2.5	3.7
Laboratories	0.5	1.5	5.0	3.6	2.9	6.0
Medical offices	0.5	0.7	3.5	3.1	1.9	1.6
Operating theatres	7.1	8.1	10.5	11.8	6.2	10.6
Administrative offices	0.5	0.7	3.4	0.6	1.9	1.3
Connective spaces	0.5	0.5	3.1	1.2	0.3	0.3
Kitchens and canteens	0.6	11.7	3.1	1.4	0.3	0.3
Mortuary	–	3.5	8.7	–	5.5	1.9
Storage rooms	1.2	0.3	3.3	–	0.3	0.3
Technical spaces and services	0.8	0.4	3.6	0.8	2.9	5.6
Toilets and dressing rooms	0.5	3.6	3.0	0.6	1.4	3.9
Macro-Area						
IPUs	0.5	3.0	3.1	2.4	1.7	1.8
D&T	3.1	4.3	4.4	4.5	3.1	4.8
General services	0.6	2.0	3.3	1.0	1.1	1.3
Total average	1.5	3.1	3.6	2.8	1.9	2.4

Table 5.6. Average air change rate per hour in relation to the use of the spaces in small and large hospitals

	Average air change rate per hour $ACH^{*}(1 \cdot h^{-1})$	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	2.5	1.8
A&E	3.9	0.8
OPD	3.0	2.9
Diagnostic imaging	5.5	2.9
Laboratories	3.1	5.0
Medical offices	2.5	1.8
Operating theatres	9.7	9.6
Administrative offices	1.6	1.5
Connective spaces	1.8	0.3
Kitchens and canteens	3.7	0.3
Mortuary	2.7	3.3
Storage rooms	1.4	0.3
Technical spaces and services	1.7	4.6
Toilets and dressing rooms	1.8	3.1
Macro-Area		
IPUs	2.5	1.8
D&T	4.3	4.2
General services	2.0	1.3
Total average	3.0	2.2

Air flow rate for natural and mechanical ventilation of the six hospitals considered evaluated in relation to the functional areas are reported in Appendix B, table B.7 and table B.8.

6 Discussion of the results

In this section the findings regarding specific energy consumption for transmission, ventilation and humidification reported in section 4.3 are interpreted and discussed in light of the variables affecting these type of energy use, that are the average thermal transmittance and the average air change rates per hour, defined and calculated in section 5.1.1 and 5.1.2. The energy consumption analysis and forecasting model developed in section 5 can thus be validated.

Furthermore, for a deeper understanding of each end-use energy consumption, results regarding energy use per unit conditioned floor area are also discussed in light of the analysis of the distribution of the conditioned floor area by functional areas reported in section 3.

Taking into account specific energy consumption for transmission, reported in Table 4.19-4.20 and in Figure 4.4, it was found that administrative offices and toilets and dressing rooms present the highest energy consumption per unit conditioned floor area per year. Indeed, the analysis of the average thermal transmittance (Table 5.1-5.2) underlines that administrative offices are among the spaces with the highest value.

However, for sake of completeness, it is necessary to underline that, while administrative offices and toilets and dressing rooms represent a small portion of hospital conditioned floor area, ranging from 2% to 6%, IPUs occupy the highest amount of conditioned floor area, equal to about 33% (see section 3, Table 3.1 and Figure 3.1). Furthermore, being mainly located along the building perimeter in order to receive natural light, IPUs are characterised by the highest external surface, from 22% to 26%. For this reason, results regarding the percentage distribution of energy consumption for transmission by type of space, reported in Table 4.21-4.22 and in Figure 4.5, illustrate that IPUs are the most energy-consuming functional area. They contribute from 24% to 34% to total energy consumption for transmission in small and large hospitals respectively.

The analysis of the findings related to specific energy consumption for natural ventilation, outlined in Table 4.23-4.24 and Figure 4.6, shows that the functional areas with the highest specific energy use are A&E, OPD and technical spaces and services. The same trend can be observed when analysing the spaces with the highest average air change rates per hour for natural ventilation, reported in Table 5.3.

Nevertheless, taking into consideration the percentage distribution of energy consumption, IPUs are responsible for the highest energy use, ranging from 30% up to 40%, followed by OPD and connective spaces (see Table 4.25-4.26 and Figure 4.7), owing to the distribution of the conditioned floor area in relation to the use of the spaces.

Considering the specific use of energy for mechanical ventilation (Table 4.27-4.28 and Figure 4.8), the values obtained underline that operating theatres have the highest specific energy consumption, followed by laboratories. This is due to the necessity of high air change rates per hour and the strict mandatory requirements for microclimatic control set by regulation for these functional areas. Indeed, taking into account the average air change rates per hour for mechanical ventilation, illustrated in Table 5.4, exactly the same functional areas emerge.

However, the percentage distribution of energy consumption reported in Table 4.29-4.30 and in Figure 4.9 shows that, besides operating theatres, also IPUs are the most energy-consuming functional area. Each of them is responsible for about 28% of energy use, followed by laboratories and OPD.

As energy consumption for humidification depends on the same parameter as energy use for mechanical ventilation, that is the average air change rate per hour for mechanical ventilation (eqs. 6 and 7 outlined in section 4.2.1), it follows that the functional areas characterised by the highest specific use of energy for mechanical ventilation also present the highest energy consumption for humidification, as it can be inferred by comparing Table 4.27 and Table 4.31. Likewise, the trend observed by considering the percentage distribution of energy consumption for mechanical ventilation is the same as the one that emerges when analysing the percentage distribution of energy used for humidification, as illustrated in Table 4.29 and Table 4.33.

A summary of the results obtained in the work is reported in the following charts, where are illustrated the average thermal EUI and the percentage distribution of thermal energy consumption by functional area (Figures 6.1-6.2) and by end use (Figure 6.3).

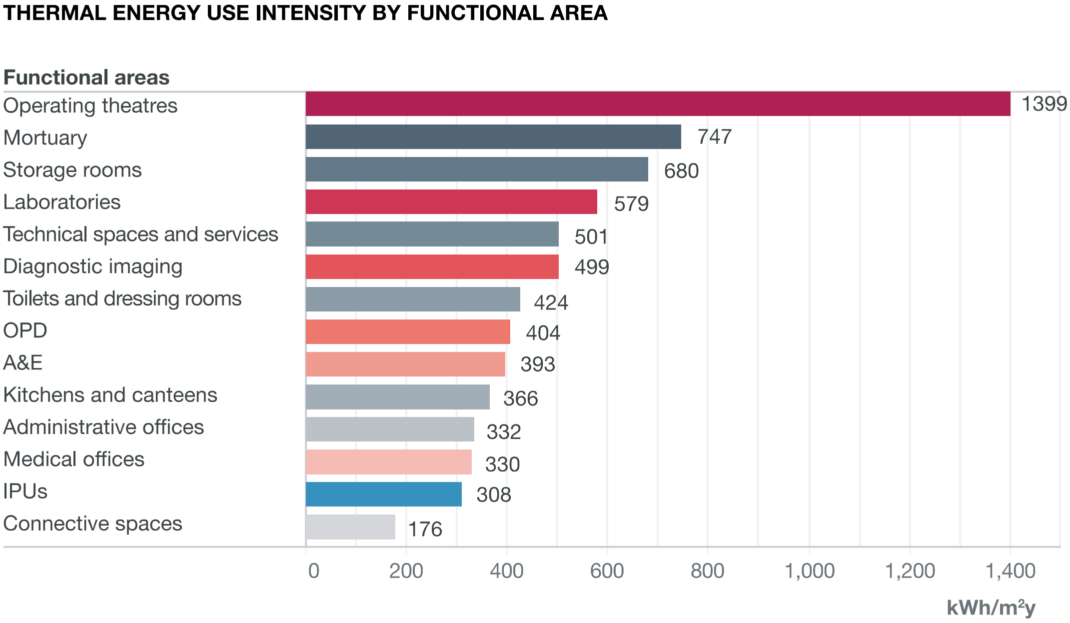

Figure 6.1. Average thermal EUI by functional area

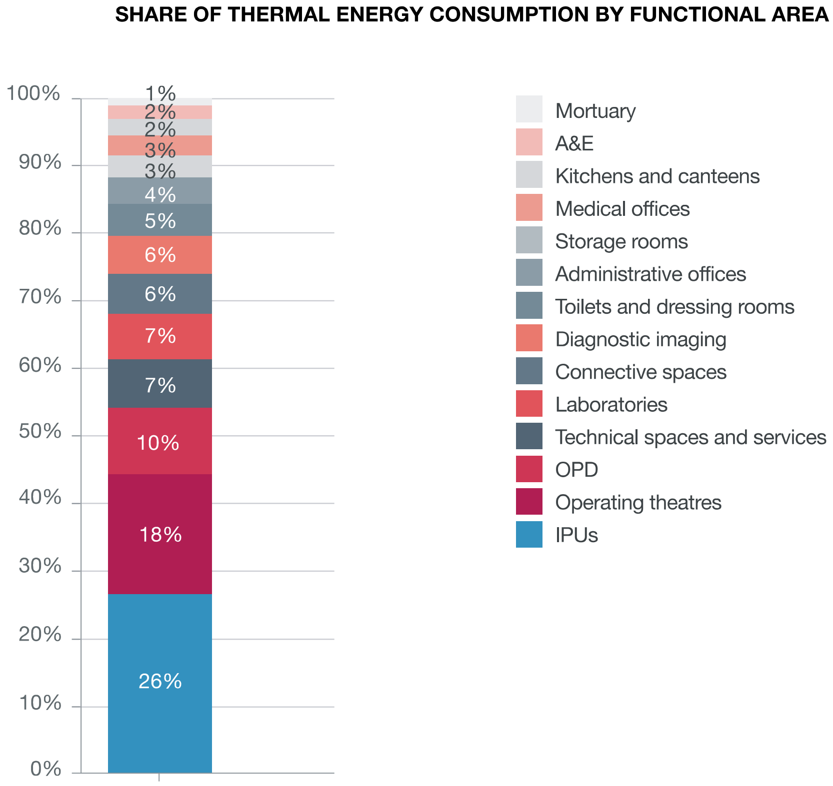

Figure 6.2. Share of total thermal energy consumption by functional area

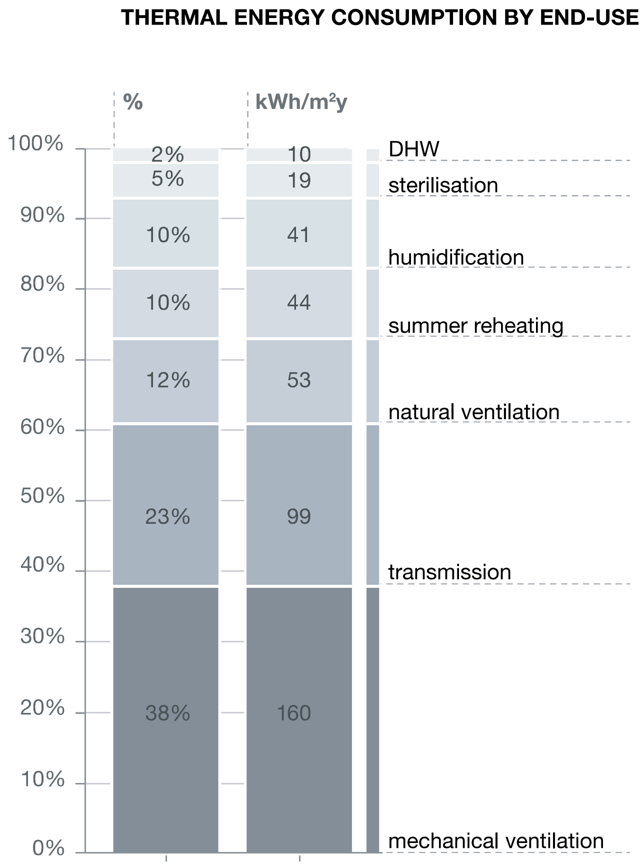

Figure 6.3. Average thermal energy consumption by end-use expressed both as a percentage and per unit conditioned floor area

Study results underline that operating theatres are the functional area with the highest thermal EUI (Figure 6.1), as observed in section 4.3 (see Table 4.13 and Figure 4.2). Furthermore, the analysis of the percentage distribution of energy consumption by functional area (in light of the analysis of the distribution of the conditioned floor area) outlines that operating theatres are the second most energy-consuming space type too (Figure 6.2).

Conversely, while IPUs present the second lowest value of EUI (Figure 6.1), they are the first most energy-intensive functional area, due to the fact that they occupy the highest amount of conditioned floor area, equal to about 33% (see section 3, Table 3.1 and Figure 3.1).

As regards energy consumption by end use, mechanical ventilation is responsible for the highest contribution to the total energy use, equal to 38%, which is nearly twice energy consumption for transmission, equal to 23%. Taking into consideration that 1kWh is equal to about 10 Nm3 of natural gas consumed, it is clear that energy savings on mechanical ventilation allows to achieve the highest positive results in both energy and economic terms, while a reduction in transmission energy consumption will have a significantly lower impact.

The data-driven numerical model developed in this work allows to automatically elaborate the charts outlined above, which enable hospital energy managers to immediately define the most effective energy saving interventions and measures.

7 Conclusions and future developments

Analysis and discussion of the results presented in the previous section underline that, whilst the model is highly robust and reliable when considering energy consumption for ventilation, as this mainly depends on air change rates per hour, it allows to analyse and predict energy consumption for transmission with a lower degree of precision, since this is affected not only by thermal transmittance, but also by the S/V ratio.

Nevertheless, the research findings summarised in Figure 6.3 outline that the contribution of energy use for transmission to the overall hospital energy consumption is decisively small (23%) compared to energy consumption for mechanical ventilation (38%), which results to be the main responsible of hospital energy use. Furthermore, with increasingly efficient building envelopes, as well as the ever more strict mandatory requirements for microclimatic control, this discrepancy will steadily rise.

For these reasons, the data-driven model developed represents an innovative tool for the assessment and forecasting of hospital thermal energy consumption. Indeed, the review of the existing studies available in literature and illustrated in section 1.3 uncovered a series of critical issues regarding models for hospital energy use assessment and prediction.

Firstly, the shortage of works taking into consideration all hospital medical functions and use of the spaces. Secondly, the absence of studies examining large samples of whole existing operative structures. Indeed, energy analyses are still rarely based primarily on measurement data. Thirdly, a lack of studies exploring hospital energy performance by carefully considering the huge domain of the affecting factors.

The energy analysis and forecasting data-driven model defined in this work, based on six operative hospitals, takes into account morphological and architectural features, medical functions, type of HVAC system, operating hours, etc., thus representing an innovative and comprehensive energy analysis method. Moreover, omitting complex dynamic modeling, the model is a tool as simple as possible, which enables fast obtaining of fairly reliable results.

In view of the fast-paced technological advancements in healthcare delivery, the findings reported in section 4.3, besides identifying the most energy-intensive functional areas, underline the importance to develop further observation about how energy consumed by these types of spaces will change in the future. Indeed, the steady evolution in the procedures of care delivery requires the continuous remodelling of healthcare environments, with a deep impact on the related energy consumption.

The analysis of thermal energy use intensity (EUI) in relation to the use of the spaces outlined that operating theatres, besides being responsible for the highest thermal EUI, are characterised by an EUI in large-sized facilities which is twice the EUI of operating theatres in small-size hospitals (Figure 4.2). For a proper interpretation of this data, the end-use EUI breakdown of operating theatres (see Figures 4.4-4.6-4.8) is reported in the following chart. Figure 7.1 illustrates that the significant discrepancy between EUI in large-sized hospitals and EUI in small-sized structures is due to mechanical ventilation, which presents a decisively high EUI in large facilities. Indeed, these ones are characterised by increasingly technologically advanced surgery, which imposes stricter requirements for microclimatic control and higher ventilation rates. Taking into consideration the steady improvement in healthcare, this observation uncovers that EUI of operating theatres will further increase in the future.

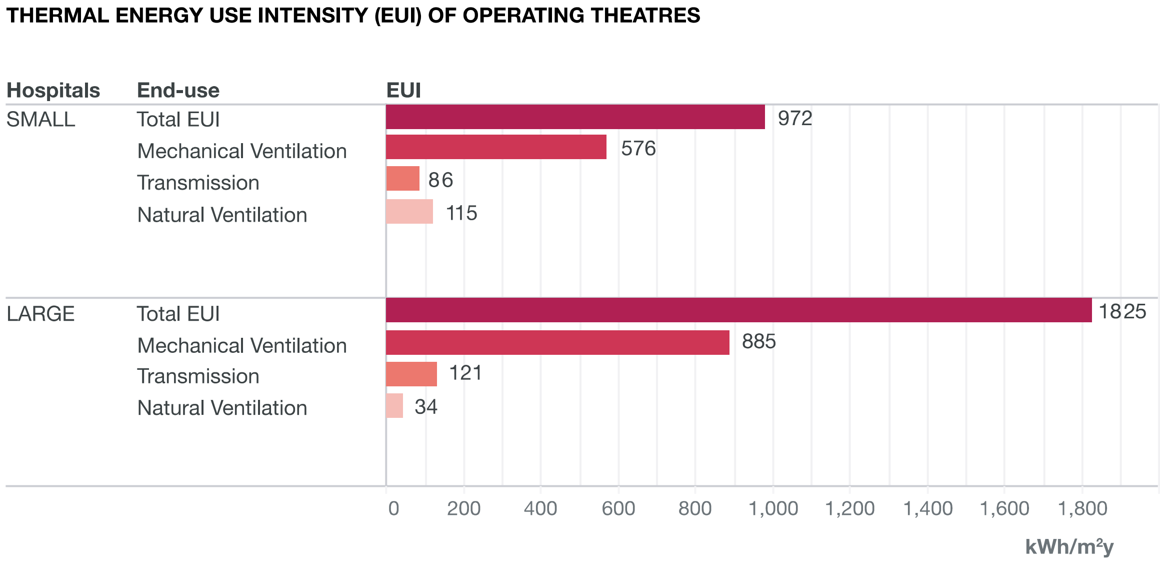

Figure 7.1. Total thermal EUI and end-use EUI breakdown of operating theatres

Similarly to operating theatres, laboratories are one of the functional areas that are being addressed by a deep process or reorganisation of hospital spaces. Indeed, diagnostic laboratories are being grouped at regional level to form single large diagnostic laboratory centres, leaving empty a large amount of spaces which can be used for other functions, with the related impact on energy consumption.

Furthermore, despite the findings reported in section 3 outlines that IPUs are the first contributor to the distribution of the conditioned floor area and of external surface, therefore being responsible for the highest percentage of energy consumed for transmission (section 4.3, Figure 4.5), the progress of medical techniques and the use of new pain medications and antibiotics are allowing to significantly reduce the patient length of stay. This process, together with the financial and economic crisis and the political pressure to reduce healthcare expenditures, is bringing to a reduction in hospital beds. Spaces previously destined for patient rooms, and IPUs in general, are decreasing in favor of non-clinical spaces and general services, completely changing energy consumption profiles.

For a deeper understanding of the importance of assessing and forecasting hospital energy consumption, it is necessary to underline that global health expenditure accounts for about 10% of the Gross Domestic Product (GDP), with Italy reaching 8.9 % of GDP and the United States spending the most of any nation by far on its healthcare system (17.1%), as already mentioned in section 1.2.

Within the economic budget of a healthcare facility, energy consumption represents a small percentage, equal to about 3%, but is responsible for a decisively higher value in absolute terms, reaching a few million euros, requiring resources that could have been used for other healthcare purposes. Albeit energy costs are often seen as fixed costs, in the financial performance of the hospital every euro saved in energy and operating costs is equal to generating about 20 euros growth in new top line revenues (ASHRAE, 2009). Therefore, while hospital budgets are getting tighter and political pressure to reduce healthcare expenditures is increasing, energy savings can be viewed as an ongoing, high yield, low risk investment or revenue stream that enable to reduce costs without impacting medical services.

Furthermore, the ability to evaluate and forecast energy usage in hospital buildings does not only allow to develop and implement energy saving measures, cut costs and invest saved resources to improve healthcare. As reported in section 1.1, Table 1.1, for each kWh of electricity or natural gas consumed, 0.28 and 0.18 kilograms carbon dioxide equivalent (kgCO2e) are released respectively. Therefore, hospital energy reduction also enables to cut healthcare-related carbon emissions, equal to nearly 5% of the national CO2 footprint in OECD countries (Eckelman, 2016).

Against this background, the data-driven model for the assessment and forecasting of hospital thermal energy consumption developed in this work represents a robust and reliable instrument both for energy saving and for environmental impact reduction.

A software based on the research outputs obtained is going to be developed within the next months in order to make the model more accessible and easier to use by managers, engineers, architects and technical staff employed in hospitals.

As a result of the extensive use of increasingly advanced medical and computing/communication equipment, as well as more ventilation and comfort cooling, healthcare facilities are facing a rise in electricity use (Christiansen et al., 2016; Christiansen et al., 2015; Morgenstern et al., 2016; Rohde & Martinez, 2015), together with a critical uncertainty in its assessment.

Although a growing number of studies have been focusing on hospital electricity consumption (Bagnasco et al., 2015; Zorita), still few works provide detailed information based on measured data at departmental level. Among these, most of the works available in literature have focused only on some hospital spaces and/or on some type of electricity end-use (Christiansen et al., 2016;

Christiansen et al., 2015; Morgenstern et al., 2016; Rohde & Martinez, 2015). Within this background, a reliable and robust assessment of hospital electricity consumption is becoming more and more important (Christiansen et al., 2016).

For this reason, one of the future developments of the work, which is going to be widen to other national healthcare facilities, is addressing this issue. The aim is to define composite benchmarks for hospitals by taking into account differing energy intensities at a departmental level. Furthermore, being based on larger sample sizes, the work will increase the reliability of the established consumption figures. Such an approach will enable to accommodate the fast-moving changes in healthcare delivery – and their impacts on layout features of hospital interior spaces – as well as the large heterogeneity between hospital buildings.

Albeit focussed on hospital buildings, the methodology developed has a much wider utility as it could be applied to other non-residential building types in temperate climates, even thanks to its ease of use.

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Appendix A

This appendix illustrates the findings reported as a percentage in section 3, here expressed in absolute values. They have been used to calculate the theoretical electricity savings potentials presented in section 5.4.

Table A.1. Distribution of the conditioned floor area in relation to the use of the spaces in hospitals with a compact form and in those with an articulated one

	Conditioned floor area (m^2)							
	Hospitals with a compact form				**Hospitals with an articulated form**			
Functional area	**A**	**C**	**F**	**IDL***	**B**	**D**	**E**	**IDL***
IPUs	1,037	2,192	30,115	14,676	1,577	4,452	17,899	19,998
A&E	88	690	1,143	1,901	225	396	0	1,873
Medical offices	131	410	2,317	5,158	315	662	2,191	4,889
Administrative offices	336	341	6,893		364	552	3,072	
Laboratories	72	231	3,941	1,607	416	636	2,116	1,603
Operating theatres	90	473	3,887	4,248	311	567	1,568	4,201
OPD	487	467	7,504	168	643	2,382	4,426	0
Diagnostic imaging	150	343	3,885	2,666	245	431	4,414	2,592
Kitchens and canteens	213	236	3,433	1,052	259	471	1,093	1,052
Mortuary	0	46	498	0	73	0	357	0
Toilets and dressing rooms	135	411	2,818	0	116	478	1,922	0
Connective spaces	460	1,677	19,638	9,100	903	1,771	7,816	5,410
Storage rooms	41	275	1,037	1,319	222	0	1,441	1,335
Technical spaces and services	145	394	3,014	4,059	365	366	2,472	4,105
Macro-Area								
IPUs	1,037	2,192	30,115	14,676	1,577	4,452	17,899	19,998
D&T	1,263	2,482	25,682	13,292	2,154	5,059	16,218	10,269
General services	1,084	3,512	34,324	24,759	2,302	3,654	16,669	16,791
Total	3,385	8,185	90,121	45,954	6,033	13,165	50,786	47,058

* Burpee & Loveland (2010

Table A.2. Distribution of the conditioned floor area in relation to the use of the spaces in small and large hospitals

	Conditioned floor area (m^2)							
	Small hospitals				**Large hospitals**			
Single space	**A**	**B**	**C**	**TSD***	**D**	**E**	**F**	**TSD****
Patient rooms	570	816	1,206	574	2,047	5,157	11,186	9,151
A&E specific spaces	68	70	25	43	140	0	140	637
Medical offices	184	394	453	1,321	838	4,252	6,121	8,036
Administrative offices	213	440	511		908	2,646	4,791	
Laboratories	72	312	231	125	513	1,426	2,260	1,169
ORs and support spaces	239	171	182	429	249	1,610	2,671	2,957
Consulting/Examination rooms	259	566	755	341	1,605	3,074	5,322	1,760
Diagnostic/Examination rooms	64	132	161	95	180	1,507	1,539	1,043
Kitchen and canteen specific spaces	126	246	218	206	304	896	2,370	830
Mortuary and support spaces	0	56	104	0	0	180	441	0
Toilets and dressing rooms	314	525	844	291	1,198	4,870	7,720	213
Connective spaces	966	1,720	2,633	1,391	4,515	18,214	36,058	5,919
Storage rooms	156	201	444	523	68	3,602	4,903	3,945
Technical spaces and services	154	383	419	638	601	3,353	4,599	2,271
Macro-Area								
IPUs	570	816	1,197	574	2,047	5,157	11,186	9,151
D&T	886	1,645	1,806	1,032	3,524	11,869	18,053	7,565

General services	1,929	3,572	5,182	4,370	7,593	33,760	60,882	21,213
Total	3,385	6,033	8,185	5,976	13,165	50,786	90,121	37,930

* Bonnema et al. (2010a)

** Bonnema et al. (2010b)

Table A.3. Distribution of the external surface in relation to the building envelope components in hospitals with a compact form and in hospitals with an articulated one

	External surface (m2)							
	Hosp. with a compact form				**Hosp. with an articulated form**			
Building envelope component	**A**	**C**	**F**	**IDL***	**B**	**D**	**E**	**IDL***
N windows	114	213	2,558	13,448	0	376	1,853	14,787
NE windows	0	5	889	0	176	0	227	0
NW windows	0	76	1,117	0	222	0	500	0
E windows	82	387	727	9,829	0	429	1,067	21,494
S windows	136	195	2,769	12,655	0	387	1,907	19,509
SE windows	0	39	1,125	0	194	0	448	0
SW windows	0	12	721	4,138	80	0	209	0
W windows	126	332	735	3,842	0	312	1,051	22,242
Skylights	0	0	6	0	14	0	16	0
Overall Windows	458	1,259	10,765	43,911	704	1,519	7,417	78,032
Opaque components	4,158	11,330	88,868	335,492	8,140	18,400	65,996	449,677
Total	4,616	12,588	99,633	379,403	8,844	19,919	73,414	527,709

* Burpee & Loveland (2010

Table A.4. Distribution of the external surface at functional area level

	External surface (m2)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	1,014	1,321	2,781	5,105	23,310	22,215
A&E	186	374	481	676	0	1,374
OPD	510	1,244	791	3,732	5,924	8,062
Diagnostic imaging	285	267	615	736	6,316	3,207
Laboratories	97	678	405	947	2,531	5,999
Medical offices	151	404	856	934	3,531	3,283
Operating theatres	587	537	542	589	3,770	6,609
Administrative offices	161	666	1,066	1,019	3,054	7,190
Connective spaces	645	1,325	2,489	3,779	11,908	22,986
Kitchens and canteens	441	544	525	917	2,126	7,333
Mortuary	0	150	84	0	313	366
Storage rooms	77	364	599	0	2,611	1,846
Technical spaces and services	185	702	580	578	4,122	3,515
Toilets and dressing rooms	277	267	773	908	3,898	5,649
Macro-Area						
IPUs	1,014	1,321	2,781	5,105	23,310	22,215
D&T	1,817	3,504	3,691	7,614	22,071	28,533
General services	1,785	4,019	6,117	7,200	28,032	48,885
Total	4,616	8,844	12,588	19,919	73,414	99,633

Table A.5. Distribution of the external surface at functional area level in small and large hospitals

	External surface (m2)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	2,555	22,763
A&E	429	1,374
OPD	1,569	6,993
Diagnostic imaging	476	4,762
Laboratories	532	4,265
Medical offices	586	3,407
Operating theatres	564	5,189
Administrative offices	728	5,122
Connective spaces	2,059	17,447
Kitchens and canteens	607	4,729
Mortuary	117	340
Storage rooms	347	2,229
Technical spaces and services	511	3,818
Toilets and dressing rooms	556	4,774
Macro-Area		
IPUs	2,555	22,763
D&T	4,157	25,989
General services	4,925	38,459
Total	11,637	87,210

Table A.6. Distribution of the external surface at single space level

	External surface (m2)					
Single space	**A**	**B**	**C**	**D**	**E**	**F**
Patient rooms	620	686	1,835	2,298	7,183	8,100
A&E specific spaces	162	134	16	220	0	280
Consulting/Examination rooms	308	858	1,015	2,395	4,188	6,085
Diagnostic/Examination rooms	126	135	287	316	2,115	1,246
Laboratories	97	523	405	762	1,760	3,293
Medical offices	229	549	981	1,197	6,531	6,864
ORs and support spaces	377	285	236	243	2,264	2,266
Administrative offices	293	722	1,074	1,480	4,669	8,460
Connective spaces	1,174	2,255	3,176	7,490	23,717	35,933
Kitchen and canteen specific spaces	245	510	462	544	1,688	5,009
Mortuary and support spaces	0	122	167	0	207	313
Storage rooms	267	321	797	142	6,012	5,882
Technical spaces and services	202	726	688	867	5,446	5,068
Toilets and dressing rooms	505	1,019	1,448	1,965	7,633	10,834
Macro-Area						
IPUs	620	686	1,818	2,298	7,183	8,100
D&T	1,299	2,484	2,941	5,132	16,857	20,033
General services	2,697	5,674	7,829	12,488	49,373	71,500
Total	4,616	8,844	12,588	19,919	73,414	99,633

Table A.7. Distribution of the external surface at single space level in small and large hospitals

	External surface (m2)	
Single space	**Small Hospital**	**Large Hospital**
Patient rooms	1,360	7,642
A&E specific spaces	133	280
Consulting/Examination rooms	1,144	5,137
Diagnostic/Examination rooms	216	1,680
Laboratories	447	2,526
Medical offices	739	6,697
ORs and support spaces	285	2,265
Administrative offices	892	6,564
Connective spaces	3,524	29,825
Kitchen and canteen specific spaces	440	3,349
Mortuary and support spaces	144	260
Storage rooms	382	5,947
Technical spaces and services	621	5,257
Toilets and dressing rooms	1,237	9,234
Macro-Area		
IPUs	1,360	7,642
D&T	2,964	18,585
General services	7,240	60,436
Total	11,564	86,663

Table A.8. Distribution of the external surface of external walls at functional area level

	External surface of external walls (m2)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	615	397	1,342	1,400	8,050	11,546
A&E	19	57	355	131	0	426
OPD	285	519	231	887	1,803	2,376
Diagnostic imaging	111	25	151	146	1,995	1,289
Laboratories	32	177	133	181	1,050	1,611
Medical offices	98	131	314	290	1,339	1,646
Operating theatres	169	136	49	291	769	1,942
Administrative offices	56	169	323	253	1,046	2,403
Connective spaces	167	186	670	813	2,872	5,901
Kitchens and canteens	110	108	209	88	710	906
Mortuary	0	18	17	0	122	179
Storage rooms	15	121	158	0	590	455
Technical spaces and services	102	202	247	166	1,111	936
Toilets and dressing rooms	102	55	243	280	844	1,281
Macro-Area						
IPUs	615	397	1,342	1,400	8,050	11,546
D&T	715	1,044	1,232	1,926	6,956	9,291
General services	550	859	1,866	1,600	7,295	12,062
Total	1,880	2,300	4,440	4,926	22,302	32,900

Table A.9. Distribution of the external surface of external walls at functional area level in small and large hospitals

	External surface of external walls (m2)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	939	9,798
A&E	141	426
OPD	481	2,090
Diagnostic imaging	108	1,642
Laboratories	131	1,331
Medical offices	208	1,493
Operating theatres	161	1,355
Administrative offices	200	1,724
Connective spaces	459	4,387
Kitchens and canteens	129	808
Mortuary	17	151
Storage rooms	98	523
Technical spaces and services	179	1,024
Toilets and dressing rooms	170	1,063
Macro-Area		
IPUs	939	9,798
D&T	1,229	8,337
General services	1,252	9,679
Total	3,420	27,814

Table A.10. Distribution of the external surface of external walls at single space level

	External surface of external walls (m_2)					
Single space	**A**	**B**	**C**	**D**	**E**	**F**
Patient rooms	385	290	869	817	3,026	4,909
A&E specific spaces	14	35	7	58	0	67
Consulting/Examination rooms	195	251	489	726	1,552	2,306
Diagnostic/Examination rooms	58	6	75	83	662	469
Laboratories	32	148	133	181	719	1,110
Medical offices	138	162	377	387	2,723	3,398
ORs and support spaces	129	57	22	123	476	631
Administrative offices	130	173	348	366	1,860	2,687
Connective spaces	277	292	785	1,313	5,267	10,525
Kitchen and canteen specific spaces	66	97	172	68	597	660
Mortuary and support spaces	0	18	27	0	74	154
Storage rooms	97	102	253	7	1,702	1,598
Technical spaces and services	108	208	279	234	1,517	1,455
Toilets and dressing rooms	250	460	604	562	2,128	2,932
Macro-Area						
IPUs	385	290	868	817	3,026	4,909
D&T	567	660	1,103	1,558	6,131	7,980
General services	928	1,350	2,470	2,551	13,145	20,011
Total	1,880	2,300	4,440	4,926	22,302	32,900

Table A.11. Distribution of the external surface of external walls at single space level in small and large hospitals

	External surface of external walls (m_2)	
Single space	**Small Hospital**	**Large Hospital**
Patient rooms	590	3,967
A&E specific spaces	29	67
Consulting/Examination rooms	415	1,929
Diagnostic/Examination rooms	55	565
Laboratories	124	914
Medical offices	266	3,060
ORs and support spaces	83	553
Administrative offices	254	2,274
Connective spaces	667	7,896
Kitchen and canteen specific spaces	101	628
Mortuary and support spaces	22	114
Storage rooms	115	1,650
Technical spaces and services	208	1,486
Toilets and dressing rooms	469	2,530
Macro-Area		
IPUs	590	3,967
D&T	972	7,089
General services	1,836	16,578
Total	3,398	27,634

Table A.12. Distribution of the external surface of windows at functional area level

	External surface of windows (m_2)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	140	126	446	470	3,168	4,140
A&E	20	6	126	50	0	165
OPD	49	92	52	291	544	1,179
Diagnostic imaging	14	8	39	53	568	406
Laboratories	9	82	41	69	311	587
Medical offices	15	80	84	93	413	332
Operating theatres	13	15	24	42	222	634
Administrative offices	50	102	82	50	362	653
Connective spaces	94	76	175	290	962	1,328
Kitchens and canteens	22	28	42	44	246	663
Mortuary	0	1	6	0	28	36
Storage rooms	8	21	21	0	121	130
Technical spaces and services	17	33	66	36	282	280
Toilets and dressing rooms	7	33	55	31	191	234
Macro-Area						
IPUs	140	126	446	470	3,168	4,140
D&T	121	284	365	597	2,057	3,303
General services	197	294	448	452	2,192	3,323
Total	458	704	1,259	1,519	7,417	10,765

Table A.13. Distribution of the external surface of windows at functional area level in small and large hospitals

	External surface of windows(m_2)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	295	3,654
A&E	53	165
OPD	119	861
Diagnostic imaging	28	487
Laboratories	50	449
Medical offices	68	373
Operating theatres	24	428
Administrative offices	71	507
Connective spaces	159	1,145
Kitchens and canteens	34	454
Mortuary	4	32
Storage rooms	17	126
Technical spaces and services	38	281
Toilets and dressing rooms	32	213
Macro-Area		
IPUs	295	3,654
D&T	342	2,762
General services	354	2,758
Total	991	9,174

Table A.14. Distribution of the external surface of windows at single space level

	External surface of windows (m^2)					
Single space	**A**	**B**	**C**	**D**	**E**	**F**
Patient rooms	73	97	249	267	947	1,754
A&E specific spaces	20	6	9	13	0	26
Consulting/Examination rooms	32	85	125	218	524	1,085
Diagnostic/Examination rooms	5	3	12	31	139	162
Laboratories	9	67	41	69	251	413
Medical offices	26	92	114	136	872	1,289
ORs and support spaces	9	7	8	13	120	216
Administrative offices	59	98	100	98	594	935
Connective spaces	130	111	217	461	2,227	2,349
Kitchen and canteen specific spaces	17	27	33	37	223	523
Mortuary and support spaces	0	1	5	0	19	30
Storage rooms	22	18	48	4	378	599
Technical spaces and services	19	36	93	64	471	526
Toilets and dressing rooms	37	56	205	108	652	858
Macro-Area						
IPUs	73	97	243	267	947	1,754
D&T	101	260	309	480	1,906	3,190
General services	285	347	707	772	4,564	5,820
Total	458	704	1,259	1,519	7,417	10,765

Table A.15. Distribution of the external surface of windows at single space level in small and large hospitals

	External surface of windows(m^2)	
Single space	**Small Hospital**	**Large Hospital**
Patient rooms	172	1,351
A&E specific spaces	12	26
Consulting/Examination rooms	115	804
Diagnostic/Examination rooms	13	151
Laboratories	47	332
Medical offices	92	1,081
ORs and support spaces	9	168
Administrative offices	89	764
Connective spaces	230	2,288
Kitchen and canteen specific spaces	29	373
Mortuary and support spaces	3	25
Storage rooms	23	489
Technical spaces and services	53	499
Toilets and dressing rooms	102	755
Macro-Area		
IPUs	172	1,351
D&T	287	2,562
General services	527	5,192
Total	986	9,104

Appendix B

This appendix illustrates the theoretical energy needs for transmission and the air flow rate for natural and mechanical ventilation in relation to the functional areas of the six hospitals considered.

They have been used to calculate energy consumption for transmission, ventilation and humidification in dynamic conditions presented in section 4.3, on the base of equations outlined in section 4.2.1.

Table B.1. Theoretical energy demand for transmission at functional area level

Functional area	Theoretical energy demand for transmission (W)						
	A		B	C	D	E	F
	pre-ins.	post ins.					
IPUs	45,974	24,013	40,242	147,628	129,039	701,380	706,663
A&E	5,358	4,730	11,131	31,695	16,266	–	36,177
OPD	19,522	10,050	36,416	21,559	82,394	168,470	163,520
Diagnostic imaging	6,983	4,004	3,261	19,345	16,913	168,574	52,890
Laboratories	2,530	1,621	19,520	15,977	25,665	63,737	123,939
Medical offices	6,166	3,235	14,466	31,713	26,297	96,037	69,535
Operating theatres	16,426	12,003	16,403	13,441	19,160	62,780	117,172
Administrative offices	8,260	6,646	20,510	42,094	23,686	107,463	188,116
Connective spaces	22,299	17,291	32,020	86,857	102,743	218,074	382,929
Kitchens and canteens	8,272	6,172	12,937	25,739	24,025	72,489	150,642
Mortuary	–	–	3,132	1,921	–	8,314	10,195
Storage rooms	2,098	1,661	10,724	15,725	–	54,265	40,537
Technical spaces and services	6,853	3,761	20,362	23,320	19,040	82,249	73,485
Toilets and dressing rooms	7,250	4,815	9,377	23,083	22,913	88,991	121,097
Macro-Area							
IPUs	45,974	24,013	40,242	147,628	129,039	701,380	706,663
D&T	56,985	35,643	101,197	133,730	186,695	559,598	563,232
General services	55,032	40,346	109,062	218,739	192,407	631,845	967,000
Total	157,991	100,002	250,501	500,097	508,141	1,892,822	2,236,895

Table B.2. Theoretical energy demand for transmission at single space level

Single space	Theoretical energy demand for transmission (W)						
	A		B	C	D	E	F
	pre-ins.	post ins.					
Patient rooms	27,947	13,834	23,716	92,322	65,697	216,870	239,135
A&E specific spaces	4,988	4,484	6,235	1,429	5,295	–	6,299
Consulting/Examination rooms	12,672	6,219	24,627	41,820	60,088	125,078	145,600
Diagnostic/Examination rooms	3,209	1,735	1,210	9,375	7,685	46,857	20,342
Laboratories	2,530	1,621	16,069	15,977	23,852	45,517	66,739
Medical offices	9,392	4,996	18,302	38,943	35,025	180,142	186,028
ORs and support spaces	10,987	6,529	9,910	5,463	7,562	39,000	44,317
Administrative offices	12,592	8,868	20,719	43,085	35,179	163,329	225,227
Connective spaces	35,830	28,805	52,961	108,805	174,465	538,073	692,272
Kitchen and canteen specific spaces	5,117	3,796	12,056	22,255	14,736	58,359	103,393
Mortuary and support spaces	–	–	2,806	2,687	–	5,755	8,491
Storage rooms	7,899	4,849	9,062	24,919	4,512	142,908	137,970
Technical spaces and services	7,455	4,160	20,942	29,616	25,126	118,467	107,948
Toilets and dressing rooms	17,373	10,106	31,886	63,401	48,919	212,466	253,134
Macro-Area							
IPUs	27,947	13,834	23,716	91,500	65,697	216,870	239,135
D&T	43,778	25,584	76,353	113,007	139,507	436,595	469,325
General services	86,266	60,584	150,432	295,590	302,937	1,239,357	1,528,436
Total	157,991	100,002	250,501	500,097	508,141	1,892,822	2,236,895

Table B.3. Theoretical energy demand for transmission through external walls at functional area level

Functional area	Theoretical energy demand for transmission through external walls (W)						
	A		B	C	D	E	F
	pre-ins.	post ins.					
IPUs	29,797	7,654	15,866	70,827	66,357	291,790	334,377
A&E	878	247	1,462	17,954	6,077	–	11,136
OPD	13,110	3,590	22,194	10,253	42,200	69,265	53,854
Diagnostic imaging	4,405	1,417	1,032	8,772	6,608	66,580	19,191
Laboratories	1,333	409	7,332	7,014	8,349	27,982	38,883
Medical offices	4,212	1,262	5,192	15,687	13,698	40,225	28,241
Operating theatres	7,916	3,482	5,522	2,634	13,591	25,517	37,658
Administrative offices	2,376	704	6,814	16,759	11,733	44,527	60,375
Connective spaces	7,805	2,688	7,770	34,154	39,413	76,993	123,353
Kitchens and canteens	3,482	1,365	4,436	10,560	4,138	30,984	25,655
Mortuary	–	–	685	534	–	3,651	4,882
Storage rooms	633	183	4,949	7,699	–	21,253	12,946
Technical spaces and services	4,368	1,255	8,224	12,242	7,470	36,456	26,524
Toilets and dressing rooms	3,743	1,304	2,183	10,148	13,256	30,769	36,985
Macro-Area							
IPUs	29,797	7,654	15,866	70,827	66,357	291,790	334,377
D&T	31,854	10,408	42,734	62,315	90,523	229,569	188,963
General services	22,407	7,500	35,061	92,097	76,010	244,634	290,718
Total	84,057	25,561	93,661	225,239	232,890	765,993	814,058

Table B.4. Theoretical energy demand for transmission through external walls at single space level

Single space	Theoretical energy demand for transmission through external walls (W)						
	A		B	C	D	E	F
	pre-ins.	post ins.					
Patient rooms	19,029	4,811	11,728	45,616	37,643	107,574	107,264
A&E specific spaces	691	185	1,462	492	2,673	–	1,062
Consulting/Examination rooms	8,938	2,448	10,131	23,322	34,133	54,066	54,302
Diagnostic/Examination rooms	2,260	779	242	4,631	3,712	21,704	7,671
Laboratories	1,333	409	6,186	7,014	8,349	19,626	23,262
Medical offices	6,200	1,772	6,581	19,152	18,197	83,813	67,656
ORs and support spaces	6,188	1,716	2,383	1,175	5,637	17,217	14,094
Administrative offices	5,443	1,646	6,981	18,344	17,239	73,076	67,167
Connective spaces	12,452	5,306	11,801	40,094	64,266	168,586	286,827
Kitchen and canteen specific spaces	2,149	815	3,970	8,850	3,178	25,286	18,728
Mortuary and support spaces	–	–	685	729	–	2,529	4,061
Storage rooms	4,272	1,201	4,246	12,272	334	60,101	42,064
Technical spaces and services	4,659	1,340	8,487	14,129	10,711	49,659	38,127
Toilets and dressing rooms	10,442	3,133	18,778	29,420	26,818	82,755	81,772
Macro-Area							
IPUs	19,029	4,811	11,728	45,532	37,643	107,574	107,264
D&T	25,610	7,309	26,985	55,785	72,701	196,426	168,047
General services	39,418	13,441	54,948	123,922	122,546	461,993	538,747

Total	84,057	25,561	93,661	225,239	232,890	765,993	814,058

Table B.5. Theoretical energy demand for transmission through windows at functional area level

	Theoretical energy demand for transmission through windows (W)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	11,909	9,851	38,728	38,946	240,600	314,908
A&E	1,638	544	10,861	3,739	–	12,627
OPD	4,205	7,750	4,318	24,233	43,804	79,023
Diagnostic imaging	1,156	729	3,336	4,329	41,929	20,134
Laboratories	799	6,871	3,622	5,541	19,934	43,686
Medical offices	1,319	6,821	7,319	7,896	30,576	25,757
Operating theatres	1,086	1,360	2,155	3,593	10,792	41,585
Administrative offices	4,310	8,376	7,100	4,169	31,497	56,986
Connective spaces	8,025	6,607	14,751	24,156	62,585	86,839
Kitchens and canteens	1,775	2,393	3,561	3,669	22,053	52,941
Mortuary	–	26	516	–	2,303	3,059
Storage rooms	686	1,805	1,809	–	8,129	10,942
Technical spaces and services	1,442	2,833	5,674	2,968	14,696	22,722
Toilets and dressing rooms	594	2,669	4,823	2,617	15,855	19,967
Macro-Area						
IPUs	11,909	9,851	38,728	38,946	240,600	314,908
D&T	10,202	24,075	31,611	49,331	147,035	222,813
General services	16,831	24,709	38,234	37,579	157,117	253,456
Total	38,943	58,635	108,572	125,856	544,752	791,177

Table B.6. Theoretical energy demand for transmission through windows at single space level

	Theoretical energy demand for transmission through windows (W)					
Single space	**A**	**B**	**C**	**D**	**E**	**F**
Patient rooms	6,192	8,077	21,625	21,671	61,900	123,868
A&E specific spaces	1,638	544	807	1,019	–	1,843
Consulting/Examination rooms	2,739	7,120	10,587	18,008	38,489	74,117
Diagnostic/Examination rooms	435	243	982	2,421	7,421	6,607
Laboratories	799	5,777	3,622	5,541	15,494	27,411
Medical offices	2,267	7,828	9,916	11,418	59,832	94,895
ORs and support spaces	774	616	714	1,126	6,660	15,069
Administrative offices	5,141	7,837	8,655	8,373	49,621	78,999
Connective spaces	10,950	8,972	18,570	38,432	169,765	161,655
Kitchen and canteen specific spaces	1,408	2,340	2,835	3,092	19,798	40,751
Mortuary and support spaces	–	26	396	–	1,606	2,128
Storage rooms	1,840	1,598	4,062	346	28,249	48,364
Technical spaces and services	1,610	3,086	8,174	5,273	27,422	39,673
Toilets and dressing rooms	3,149	4,571	17,628	9,136	58,495	75,797
Macro-Area						
IPUs	6,192	8,077	21,040	21,671	61,900	123,868
D&T	8,653	22,128	26,627	39,533	127,896	219,941
General services	24,099	28,430	60,905	64,652	354,956	447,367
Total	38,943	58,635	108,572	125,856	544,752	791,177

Table B.7. Air flow rate for natural ventilation at functional area level

	Air flow rate for natural ventilation ($m^3 \cdot h^{-1}$)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	1,678	0	17,205	7,869	13,560	23,858
A&E	684	505	1,641	1,818	0	1,152
OPD	1,509	7,085	0	5,533	3,638	5,506
Diagnostic imaging	177	3,111	0	0	3,244	2,099
Laboratories	110	1,690	0	616	1,393	3,101
Medical offices	211	579	45	2,865	1,917	2,124
Operating theatres	0	813	5,636	0	1,212	3,797
Administrative offices	149	679	3,242	794	1,846	3,876
Connective spaces	725	1,219	3,399	2,902	5,027	14619.741
Kitchens and canteens	368	1,138	2,879	806	1,314	3180.108
Mortuary	–	689	1,066	–	304	455
Storage rooms	152	173	2,542	–	916	907.977
Technical spaces and services	352	380	4,833	615	1,694	2,777
Toilets and dressing rooms	207	1,074	1,634	636	1,336	2,539
Macro-Area						
IPUs	1,678	0	17,205	7,869	13,560	23,858
D&T	2,691	13,783	7,322	10,832	11,404	17,780
General services	1,953	5,352	19,595	5,752	12,438	28,355
Total	6,322	19,135	44,121	24,453	37,402	69,994

Table B.8. Air flow rate of the AHUs at functional area level

	Air flow rate of the AHUs ($m^3 \cdot h^{-1}$)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	0	12,817	10,058	20,854	63,645	121,361
A&E	0	2,400	7,878	5,271	0	4,635
OPD	0	0	5,271	13,630	36,410	41,570
Diagnostic imaging	2,300	3,000	2,956	6,200	23,356	23,713
Laboratories	0	0	3,467	5,567	12,035	58,712
Medical offices	0	0	4,967	2,616	10,476	9,221
Operating theatres	7,191	6,000	6,920	17,607	23,970	130,840
Administrative offices	0	0	1,874	178	9,862	12,907
Connective spaces	0	0	14,887	2,826	0	572
Kitchens and canteens	0	7,000	272	1,010	0	0
Mortuary	–	0	0	–	5,257	2,392
Storage rooms	0	0	0	–	0	0
Technical spaces and services	0	0	70	202	14,555	49,322
Toilets and dressing rooms	0	0	2,020	175	4,959	30,813
Macro-Area						
IPUs	0	12,817	10,058	20,854	63,645	121,361
D&T	9,491	11,400	31,459	50,891	106,247	268,692
General services	0	7,000	19,123	4,391	34,634	96,006
Total	9,491	31,217	60,640	76,136	204,526*	486,060*

* measured by Etabeta Srl.

Appendix C

This appendix illustrates the findings regarding thermal energy consumption for the six hospitals considered reported in kWh in section 4.3, here expressed in Nm^3.

Table C.1. Total thermal energy consumption

Total thermal energy consumption	A		B	C	D	E	F
	pre-ins.	post ins.					
($Nm^3 \cdot m^{-2}\ y^{-1}$)	25	20	34	52	35	56	49
($Nm^3 \cdot m^{-3}\ y^{-1}$)	8	6	12	14	13	16	15
($Nm^3 \cdot bed^{-1}\ y^{-1}$)	946	760	2,208	3,733	2,078	5,352	5,463

Table C.2. Average total thermal energy consumption in small and large hospitals

Average total thermal energy consumption	Small Hospital	Large Hospital
($Nm^3 \cdot m^{-2}\ y^{-1}$)	36	53
($Nm^3 \cdot m^{-3}\ y^{-1}$)	12	16
($Nm^3 \cdot bed^{-1}\ y^{-1}$)	2,241	5,407

Table C.3. Total thermal energy consumption in relation to the use of the spaces

Functional area	Total thermal energy consumption* ($Nm^3 \cdot m^{-2} y^{-1}$)						
	A		B	C	D	E	F
	pre-ins.	post ins.					
IPUs	13	7	24	47	23	42	33
A&E	33	31	43	49	86	–	58
OPD	15	10	40	41	29	61	44
Diagnostic imaging	51	45	63	34	48	51	59
Laboratories	10	7	20	100	39	59	98
Medical offices	14	7	30	49	32	44	30
Operating theatres	64	60	96	121	125	192	188
Administrative offices	27	21	17	49	14	53	32
Connective spaces	14	11	10	40	26	17	12
Kitchens and canteens	12	9	96	85	32	24	17
Mortuary	–	–	62	114	–	144	79
Storage rooms	149	145	32	54	–	43	124
Technical spaces and services	16	10	15	53	24	60	94
Toilets and dressing rooms	15	10	44	38	16	46	74
Macro-Area							
IPUs	13	7	24	47	23	42	33
D&T	33	28	46	60	47	70	85
General services	22	18	27	47	28	38	33
Total average	23	18	33	51	34	49	46

* without considering DHW and sterilisation

Table C.4. Average total thermal energy consumption in relation to the use of the spaces in small and large hospitals

Functional area	Total thermal energy consumption ($Nm^3 \cdot m^{-2} y^{-1}$)	
	Small Hospital	Large Hospital
IPUs	27	38
A&E	53	–
OPD	31	53
Diagnostic imaging	49	55
Laboratories	42	78
Medical offices	31	37
Operating theatres	101	190
Administrative offices	27	43
Connective spaces	22	14
Kitchens and canteens	56	20
Mortuary	–	112
Storage rooms	–	83
Technical spaces and services	27	77
Toilets and dressing rooms	28	60
Macro-Area		
IPUs	27	38
D&T	47	77
General services	31	35
Total average	35	48

Table C.5. Thermal energy consumption by end use

Building service	Energy consumption ($Nm^3 \cdot m^{-2} y^{-1}$)						
	A		B	C	D	E	F
	pre-ins.	post ins.					
Transmission	9.6	4.7	8.2	13.8	8.1	14.4	7.3
Ventilation:							
- natural ventilation	4.7	4.7	7.9	13.5	5.1	3.3	3.1
- mechanical ventilation	7.0	7.0	12.9	18.5	15.9	17.9	21.6
- humidification	–	–	–	–	–	8.5	8.8
Summer reheating	2.0	2.0	3.8	5.4	4.6	5.2	5.4
DHW	1.5	1.5	0.9	0.9	1.2	0.9	0.8
Sterilisation	–	–	–	–	–	5.4	2.4
Total average	25	20	34	52	35	56	49

Table C.6. Average thermal energy consumption by end use in small and large hospitals

Building service	Energy consumption ($Nm^3 \cdot m^{-2} y^{-1}$)	
	Small Hospital	Large Hospital
Transmission	9.9	10.8
Ventilation:		
- natural ventilation	7.8	3.2
- mechanical ventilation	13.6	19.8
- humidification	–	8.6
Summer reheating	4.0	5.3
DHW	1.1	0.9
Sterilisation	–	3.9
Total average	36	53

Table C.7. Energy consumption for transmission in relation to the use of the spaces

Functional area	Energy consumption for transmission ($Nm^3 \cdot m^{-2} y^{-1}$) A pre-ins.	A post ins.	B	C	D	E	F
IPUs	9	3	4	16	5	15	6
A&E	14	12	10	9	9	–	8
OPD	8	2	12	10	7	12	6
Diagnostic imaging	10	4	0	12	8	14	5
Laboratories	6	3	10	16	9	13	10
Medical offices	10	3	9	18	8	14	8
Operating theatres	10	7	11	8	7	18	7
Administrative offices	22	17	12	22	9	20	14
Connective spaces	10	7	6	11	14	12	5
Kitchens and canteens	7	5	11	28	12	20	12
Mortuary	–	–	9	8	–	4	5
Storage rooms	11	8	10	13	–	16	11
Technical spaces and services	10	4	12	13	12	13	6
Toilets and dressing rooms	12	6	20	12	11	19	13
Macro-Area							
IPUs	9	3	4	16	5	15	6
D&T	9	4	10	12	8	13	7
General services	11	7	10	14	13	15	8
Total average	10	5	8	14	8	14	7

Table C.8. Average energy consumption for transmission in small and large hospitals

Functional area	Energy consumption for transmission ($Nm^3 \cdot m^{-2} y^{-1}$) Small Hospital	Large Hospital
IPUs	8	11
A&E	11	–
OPD	9	9
Diagnostic imaging	8	9
Laboratories	10	12
Medical offices	12	11
Operating theatres	9	13
Administrative offices	16	17
Connective spaces	10	8
Kitchens and canteens	14	16
Mortuary	–	5
Storage rooms	–	14
Technical spaces and services	12	9
Toilets and dressing rooms	14	16
Macro-Area		
IPUs	8	11
D&T	10	10
General services	12	11
Total average	10	11

Table C.9. Energy consumption for natural ventilation in relation to the use of the spaces

	Energy consumption for natural ventilation ($Nm^3 \cdot m^{-2} y^{-1}$)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	4	0	20	5	3	3
A&E	20	6	6	13	–	3
OPD	8	28	0	6	3	3
Diagnostic imaging	3	32	0	0	3	3
Laboratories	4	10	0	3	3	3
Medical offices	4	5	0	12	3	3
Operating theatres	0	7	41	0	4	3
Administrative offices	4	5	17	4	4	3
Connective spaces	4	3	5	5	3	3
Kitchens and canteens	4	11	30	5	4	3
Mortuary	–	24	58	–	3	3
Storage rooms	9	2	23	–	3	3
Technical spaces and services	6	3	31	5	3	3
Toilets and dressing rooms	4	24	10	4	3	3
Macro-Area						
IPUs	4	0	20	5	3	3
D&T	5	16	7	6	3	3
General services	4	6	14	4	3	3
Total average	5	8	13	5	3	3

Table C.10. Average energy consumption for natural ventilation in small and large hospitals

	Energy consumption for natural ventilation ($Nm^3 \cdot m^{-2} y^{-1}$)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	7	3
A&E	11	–
OPD	10	3
Diagnostic imaging	9	3
Laboratories	4	3
Medical offices	5	3
Operating theatres	12	3
Administrative offices	7	3
Connective spaces	4	3
Kitchens and canteens	13	3
Mortuary	–	3
Storage rooms	–	3
Technical spaces and services	11	3
Toilets and dressing rooms	10	3
Macro-Area		
IPUs	7	3
D&T	9	3
General services	7	3
Total average	8	3

Table C.11. Energy consumption for mechanical ventilation in relation to the use of the spaces

	Energy consumption for mechanical ventilation ($Nm^3 \cdot m^{-2} y^{-1}$)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	0	20	11	13	15	16
A&E	0	27	29	37	–	13
OPD	0	0	28	16	31	22
Diagnostic imaging	38	31	22	40	22	36
Laboratories	0	0	37	24	29	60
Medical offices	0	0	30	11	18	14
Operating theatres	53	48	51	88	76	109
Administrative offices	0	0	10	1	20	11
Connective spaces	0	0	22	4	0	0
Kitchens and canteens	0	68	3	6	0	0
Mortuary	–	0	0	–	50	18
Storage rooms	0	0	0	–	0	0
Technical spaces and services	0	0	0	2	27	59
Toilets and dressing rooms	0	0	12	1	12	38
Macro-Area						
IPUs	0	20	11	13	15	16
D&T	19	13	32	28	30	47
General services	0	8	14	3	9	11
Total average	7	13	18	16	18	22

Table C.12. Average energy consumption for mechanical ventilation in small and large hospitals

	Energy consumption for mechanical ventilation ($Nm^3 \cdot m^{-2} y^{-1}$)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	11	16
A&E	23	–
OPD	11	27
Diagnostic imaging	33	29
Laboratories	15	44
Medical offices	10	16
Operating theatres	60	92
Administrative offices	3	15
Connective spaces	7	0
Kitchens and canteens	19	0
Mortuary	–	34
Storage rooms	–	0
Technical spaces and services	0	43
Toilets and dressing rooms	3	25
Macro-Area		
IPUs	11	16
D&T	23	38
General services	6	10
Total average	14	20

Table C.13. Energy consumption for humidification in relation to the use of the spaces

	Energy consumption for humidification ($Nm^3 \cdot m^{-2} y^{-1}$)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	–	–	–	–	7	6
A&E	–	–	–	–	–	5
OPD	–	–	–	–	15	9
Diagnostic imaging	–	–	–	–	11	14
Laboratories	–	–	–	–	14	24
Medical offices	–	–	–	–	9	6
Operating theatres	–	–	–	–	36	44
Administrative offices	–	–	–	–	9	4
Connective spaces	–	–	–	–	0	0
Kitchens and canteens	–	–	–	–	0	0
Mortuary	–	–	–	–	23	7
Storage rooms	–	–	–	–	0	0
Technical spaces and services	–	–	–	–	13	24
Toilets and dressing rooms	–	–	–	–	6	15
Macro-Area						
IPUs	–	–	–	–	7	6
D&T	–	–	–	–	14	19
General services	–	–	–	–	4	4
Total average	–	–	–	–	8	9

Table C.14. Average energy consumption for humidification in small and large hospitals

	Energy consumption for humidification ($Nm^3 \cdot m^{-2} y^{-1}$)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	–	7
A&E	–	–
OPD	–	12
Diagnostic imaging	–	13
Laboratories	–	19
Medical offices	–	7
Operating theatres	–	40
Administrative offices	–	7
Connective spaces	–	0
Kitchens and canteens	–	0
Mortuary	–	15
Storage rooms	–	0
Technical spaces and services	–	18
Toilets and dressing rooms	–	10
Macro-Area		
IPUs	–	7
D&T	–	17
General services	–	4
Total average	–	9

Table C.15. Energy consumption for summer reheating in relation to the use of the spaces

	Energy consumption for summer reheating ($Nm^3 \cdot m^{-2}\, y^{-1}$)					
Functional area	**A**	**B**	**C**	**D**	**E**	**F**
IPUs	0	0	0	0	1	2
A&E	0	0	6	28	–	29
OPD	0	0	3	0	1	4
Diagnostic imaging	0	0	0	0	1	1
Laboratories	0	0	47	4	0	0
Medical offices	0	16	0	1	0	0
Operating theatres	0	30	21	30	59	25
Administrative offices	0	0	0	0	0	0
Connective spaces	0	0	2	3	2	3
Kitchens and canteens	0	7	24	9	0	1
Mortuary	–	30	47	–	64	45
Storage rooms	128	20	18	–	23	109
Technical spaces and services	0	0	9	6	6	3
Toilets and dressing rooms	0	0	3	0	7	4
Macro-Area						
IPUs	0	0	0	0	1	2
D&T	0	7	10	6	9	9
General services	6	4	6	8	6	7
Total average	2	4	5	5	5	5

Table C.16. Average energy consumption for summer reheating in small and large hospitals

	Energy consumption for summer reheating ($Nm^3 \cdot m^{-2}\, y^{-1}$)	
Functional area	**Small Hospital**	**Large Hospital**
IPUs	0	1
A&E	8	–
OPD	1	3
Diagnostic imaging	0	1
Laboratories	13	0
Medical offices	4	0
Operating theatres	20	42
Administrative offices	0	0
Connective spaces	1	3
Kitchens and canteens	10	1
Mortuary	–	55
Storage rooms	–	66
Technical spaces and services	4	4
Toilets and dressing rooms	1	5
Macro-Area		
IPUs	0	1
D&T	6	9
General services	6	6
Total average	4	5