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Technical Guidelines on
Energy Efficiency in Major Energy-Consuming Sectors

Energy Efficiency in Airports

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für Internationale
Zusammenarbeit (GIZ) GmbH

Imprint

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This report is the fifth in a series of publications to provide an overview and analysis of energy efficiency measures for key sectors including airports, and the manufacturing industries for pulp and paper, cement, ceramics, and glass fibers, drawing from German and international experiences and best practices.

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Tayuan Diplomatic Office Building 2-5,
14 Liangmahe South Street, Chaoyang District
100600 Beijing, P. R. China
c/o
Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
Torsten Fritsche
Köthener Str. 2
10963 Berlin

Project Management
Maximilian Ryssel, Yuan Zhen
Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Coordinated by
Helmut Berger,
ALLPLAN GmbH, Schwindgasse 10,
1040 Vienna, AUSTRIA

Authors
Nushin Shahri, Thomas Eisenhut, Manuela Farghadan
ALLPLAN GmbH

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Foreword

Dear readers, colleagues and friends,

Despite major global challenges, we have seen substantial progress in the energy transition in Germany and China in the last years. China remains the country with the world's largest installed capacity of renewable energy, whereas in Germany, the share of renewables in gross electricity consumption rose to 41.1% in 2021. But whilst the promotion and development of renewable energy plays an important role in our global measures to mitigate the negative impact of climate change, it alone would not be sufficient to protect a liveable future for humanity. To complete the necessary energy transition, it is crucial to improve energy efficiency in order to reduce greenhouse gas emissions in industry, buildings, and transport.

As part of its energy transition, the German Federal Government has set itself the target to reach climate-neutrality in all sectors by 2045. By mid-century, Germany aims to cut its primary energy consumption by 50% compared to 2008. To achieve this, Germany adopted the "efficiency first" principle, which aims at prioritising energy efficiency wherever possible.

In a similar vein, China has emphasised energy efficiency as part of its Energy Revolution Strategy (2016– 2030). The 14th Five-Year-Plan set forth by the Chinese government aims to reduce energy intensity by 13.5% and carbon intensity by 18% over the 2021-2025 period. These targets are set against the backdrop of bringing carbon emissions to a peak before 2030 and achieving carbon-neutrality by 2060.

In both countries, public buildings play an important role for the decarbonization of the building sector. Authorities can directly influence (energy) design decisions and can thus showcase the technical feasibility and economic benefits of low energy buildings. Airports, at the nexus of large-scale public buildings and transportation hubs, are of particular importance. They can reach energy consumption levels equal to those of small cities. Increasing energy efficiency in airports can thus lead to significant energy savings.

Here, international cooperation between Germany and China can play a contributing role. This report is published as part of the Sino-German Energy Partnership between the German Federal Ministry for Economic Affairs and Climate Action (BMWK), the National Development and Reform Commission (NDRC) and the National Energy Administration of the PRC (NEA), and the GIZ project "Supporting Low Carbon Development in Jiangsu Province Phase III" funded by the German Federal Government's International Climate Initiative (IKI).

The report is the fifth in a series of reports on energy efficiency measures in energy-intensive sectors. It highlights sector specific measures in airports – with a focus on heating, ventilation, air conditioning (HVAC), energy supply and management, transportation, and architecture – and discusses these according to their implementation potentials and effectiveness.

I would like to express my gratitude to all involved experts and implementing partners, especially the National Energy Conservation Center of China (NECC) and the Jiangsu Department for Ecology and Environment, for their ongoing support. I sincerely hope that this study will trigger inspiration and contribute towards finding more energy-efficient solutions that lead us to a cleaner future.

Martin Hofmann

Head of Cluster Sustainable Transition,
GIZ China

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Abbreviations

ACI	Airports Council International
ACA	Airport Carbon Accreditation
ASO	Automated System Optimization
BAT	Best Available Technology
BM	Benchmark
BMS	Building Management System
BREF	Best Available Technologies Reference Documents
BREEAM	Building Research Establishment's (BRE) Environmental Assessment Method
CEFC	Clean Energy Finance Corporation
CUP	Central Utility Plant
DG	Directorate General (General Direction)
EC	European Commission
EPI	Energy Performance Index
EEA	European Environment Agency
EIFS	Exterior Insulation Finishing System
E(M)IS	Energy (Management and) Information Systems
ETS	Emissions Trading System
EU	European Union
FDD	Fault Detection and Diagnostics
GHG	Greenhouse Gas
GJ	Gigajoule
GSE	Ground Support Equipment
HVAC	Heating, Ventilation and Air Conditioning
ICAO	International Civil Aviation Organisation
IEA	International Energy Agency
IGES	Institute for Global Environmental Strategies
ISO	International Standards Organization
JRC	Joint Research Centre
kWh	Kilowatt hour
LCC	Life Cycle Costing
LEED	Leadership in Energy and Environmental Design
MBCx	Monitoring-based commissioning
MJ	Megajoule

MWh	Megawatt hour
NGO	Non-Governmental Organization
O&M	Operation and Maintenance
PAX	Passenger
PTES	Pit Thermal Energy Storage
PV	Photovoltaics
RES	Renewable Energy Sources
R&D	Research and Development
TFC	Total Final Consumption
TRL	Technology Readiness Level
TTES	Tank Thermal Energy Storage
TU	Traffic Units
UNEP	United Nations Environment Programme
WGTES	Water Gravel Thermal Energy Storage

1 Executive Summary

These guidelines describe options and measures to increase energy efficiency in airports as an example of large-scale public buildings. Airports can reach energy consumption levels equal to that of small cities. For example, in 2019, Frankfurt Airport handled 71 million passengers and consumed around 1,300 GWh of energy. Airports also show some unique energy consumption features, the most important being high volatility relative to air and passenger traffic levels, leading to highly volatile heat loads. This volatility poses a challenge for adequate planning, dimensioning and operation of heating, ventilation and air conditioning (HVAC) systems.

Generally speaking, energy consumption at airports is strongly affected by the following factors: size of the airport (m^2), outside climate conditions (heating or cooling needs), desired comfort level in the airport, extent of services provided at the airport, operational hours and passenger numbers. Given these variables, comparing different airports in terms of energy consumption should be treated with caution. Possible energy performance indices (EPI) can refer to passengers or to the size of the airport (kWh/passenger – often written as kWh/pax – or kWh/m^2). For example, EPIs of different Greek airports range from between 4 ––18 kWh/passenger or 200 – 270 kWh/m^2.

While the energy consumption mix varies from airport to airport, electricity dominates final energy consumption in most airports. When analysing the major energy consumption areas and processes, the importance of HVAC systems becomes evident. We divide such areas into airside (excluding aircraft kerosine consumption) and landside: (1) Airside refers to everything related to aircraft operation, including landing, take-off and guiding to the apron. Typical sub-systems include the control tower, airfield lighting, radio navigation systems, firefighting buildings, hangars and weather facilities. (2) Landside energy consumption refers to the movement, processing, organisation, and control of the flow of passengers, baggage and cargo. Typical facilities common to all airports include the terminal building, the cargo building and vehicle parking areas.

The most promising energy saving potential is seen in:

- Energy-efficient HVAC
- Architectural improvement
- Energy management and control
- Energy supply efficiency and renewable energy use
- Efficient transportation of passengers and baggage

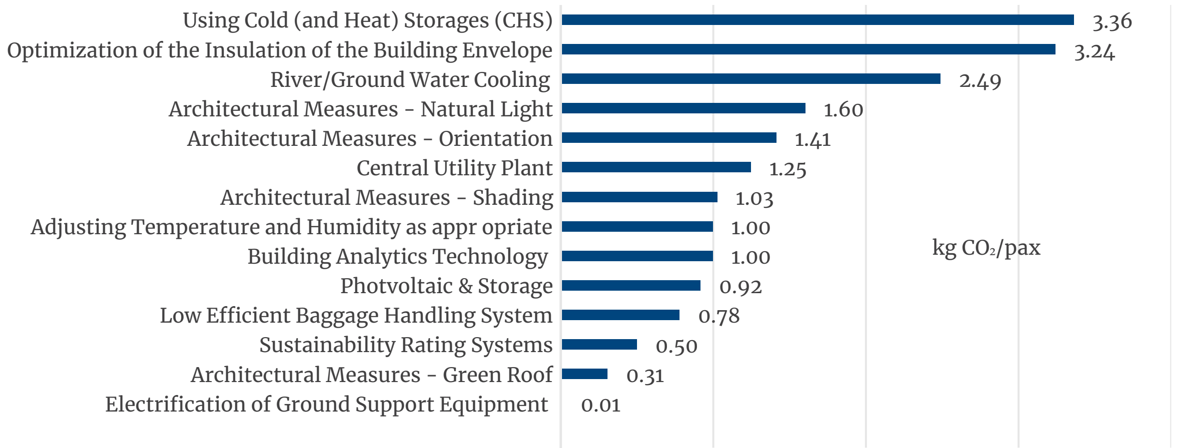
Energy efficiency and **GHG emission reduction** potential are closely linked. However, the actual impact on CO_2 emissions relies strongly on the type of **fuel** replaced and/or the primary energy source used for electricity production. This applies to all projects and measures aiming to replace fossil fuel-driven processes (transportation, boilers) with electric systems. Considering the predominantly high grid emission factors in China, the switch from fossil fuels to electricity leads to a negative CO_2 balance. However, the result can change considerably with the switch to low emission electricity sources.

Comparisons of potential energy saving measures are prone to a wide range of possible errors, as each measure assumes airport-specific baselines and different variables that should be treated on a case-by-case basis. Thus, we strongly recommend analysing the actual saving potential for specific airports and considering the average savings in terms of energy consumption for heating, cooling or electricity, respectively. For the purposes of this study, however, we use benchmarked "carbon emission reduction per capita (kg CO_2/passenger)" as an indicator to allow both an overview of and rough comparisons between the various saving measures.[1]

[1] The limited comparability of energy and emission savings provided in literature result from different baselines and airport conditions. In order to provide a single basis for comparison, the respective percentage of savings was linked to the baseline consumption of Kensai Airport (with 7.85 kg CO_2 emissions per passenger) to yield CO_2 savings per passenger.

Under these premises, Figure 1 shows a comparison that can serve as the basis when setting priorities. The comparison shows that measures targeting cooling (and heating) can lead to considerable savings.

Figure 1: Comparison of CO_2 Emissions Savings (kg/Passenger)[2]



[2] Energy and CO_2 savings are calculated based on specific assumptions (described in the respective section) and – if not otherwise specified – on IPCC emission factors for gas (0.202 t CO_2/MWh), and on the Chinese average grid emission factor of 0.618 t CO_2/MWh taken from the IGES database (https://www.iges.or.jp/en/pub/list-grid-emission-factor/en).

2 An Introduction to Energy Efficiency

This study aims to identify energy and greenhouse gas savings potential at airports via energy saving measures, or the use of renewable energy. In this chapter, general policies in Europe and Austria are discussed, specifically the Energy Performance of Buildings Directive (EPBD).

To establish a baseline, it is important to remember that although airports belong to the energy consumption sector of "buildings", their consumption characteristics are very specific. The energy consumption of an airport can reach the level of a small city and is linked to air traffic, which often times is not a constant flow, but rather a series of peaks and lows, resulting in a highly volatile energy consumption pattern. Regarding energy consumption in and around airports, it is important to analyse the most important legal and policy frameworks that apply. In Europe, these include the frameworks for energy efficiency in buildings, for renewable energy use, and for mandatory energy auditing of large enterprises.

The European Directive targeting **energy efficiency of buildings**, initially adopted in 2010 and amended in 2018,[3] has the objective of optimising the energy performance of the entire buildings sector, including large buildings such as airports. Under this Directive, member states are required to:

- Draw up a detailed national plan of their detailed application in practice of the definition of nearly zero-energy buildings
- Identify cost-effective approaches to renovation relevant to the building type and climatic zone
- Accelerate the conversion of existing buildings to ultra-low energy buildings by 2050, and ensure that all new buildings are ultra-low energy buildings from 2021
- Support the modernization of all buildings through smart technologies (Europäisches Parlament, 2022)

Regarding the practical implementation of higher energy efficiency targets, specific minimum standards are defined in the EU member countries. In Austria, the rules of the Austrian Institute of Construction Engineering (OIB) apply for new constructions and major renovations. If proof of compliance with the requirements is provided via the U-Value requirement, the following maximum values apply for non-residential buildings, such as airports:[4]

[3] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, https://eur-lex.europa.eu/eli/dir/2010/31/oj), amended 2018, Directive (EU) 2018/844 https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1529483556082&uri=CELEX%3A32018L0844

[4] https://www.oib.or.at/sites/default/files/richtlinie_6_12.04.19_1.pdf

Table 1: Minimum Building Requirements in Austria

Nr.	Building part	U-Value (W/m²K)
1	External Walls to outside air	0.35
2	Walls to unconditioned attic	0.35
3	Walls to unconditioned rooms (excluding attic) and garage	0.6
4	Walls to soil	0.4
5	Walls between residential units or non-residential units or conditioned stair cases	1.30
6	Walls to other buildings	0.50
7	External Windows, Glazed Doors to air	1.70
8	other External Transparent Building Part vertical to air	1.70
9	other External Transparent Building Part non-vertical to air	2.00
10	Other Transparent Building Part vertical to unconditioned rooms	2.50
11	Attic Windows to air	1.70
12	Doors non-glazed to outside air	1.70
13	Doors non-glazed to unconditioned rooms	2.50
14	Gates to outside air	2.50
15	Roofs to outside air	0.20
16	Ceilings to unconditioned rooms	0.40
17	Ceilings to other residential units or non-residential units	0.90
18	Ceilings over outside air	0.20
19	Ceilings to garages	0.30
20	Floors to soil	0.40

Source: OIB

In order to achieve long term decarbonisation targets, the **heat supply** also needs to be adapted accordingly. According to the Energy Performance of Buildings Directive (Article 6), for new buildings, Member States shall ensure that, "before construction of new buildings starts, the technical, environmental and economic feasibility of high-efficiency alternative systems, if available, is taken into account". These include decentralised energy supply systems based on energy from renewable sources, cogeneration, district or block heating or cooling, particularly where it is based either entirely or partially on energy from renewable sources and heat pumps.

As an example, according to Austria's current coalition agreement, a step-by-step plan should be developed, setting out the legal foundations for the replacement of oil, coal and coke-fired heating systems for indoor heating. The plan must include the following steps:

- A ban on oil heating systems for new buildings (from January 1, 2020)
- When replacing a heating system, an oil heating system is to be replaced by a climate-friendly alternative (from 2022)
- From 2025, fossil gas is to be banned in new buildings, oil heating systems that are more than 25 years old are to be successively replaced
- By 2035, all oil heating systems are to be shut down
- By 2040, the entire heat supply is to be decarbonised

The third framework for successful transition to a decarbonised economy, involves mandatory **energy audits and energy management systems**. The aim is to regularly monitor overall energy consumption, identify major energy consumers and develop energy saving measures. Large enterprises either have to implement energy (or environmental) management systems or regularly conduct energy audits every four years[5] and in compliance with the requirements of the Energy Efficiency Directive (Directive 2012/27/EU and its amendment in 2018).[6] This also applies to enterprises running airports. In general, public bodies should lead by example and prioritise reduction of CO_2 emissions and energy consumption. This is even more the case for airports that are (partly) publicly owned.

[5] Current status in Austria. The Energy Efficiency Act is currently being revised and might be expanded to include SMEs. (https://www.monitoringstelle.at/aktuelles-services/uebergangsregelungen)

[6] Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency (Text with EEA relevance.)

3 Airports and Energy Consumption

The following chapter introduces overall energy consumption areas at airports and provides a statistical overview of related figures from airports in Europe. If not otherwise specified, all figures exclude the aircraft fuel consumption.

3.1 Current Situation and Development of Energy Efficiency in the Sector

One important factor affecting the total energy consumption of airports is their size. Typical sizes of European airports in terms of passengers per year are given below (data from pre-pandemic 2019, the number of passengers per year in brackets):

- Largest European airport: London Heathrow (almost 81 million passengers)
- Paris Charles de Gaulle (76 million)
- Amsterdam (72 million)
- Frankfurt (71 million)
- Istanbul (69 million)[7]

Frankfurt Airport is one of the largest European airports. The airport consumed 1,268 GWh of energy in 2019, similar to the energy consumption of small cities.[8]

Detailed energy consumption figures are available, for example, for Vienna International Airport as depicted below. This airport had about 31 million passengers per year prior to the COVID-19 pandemic.

Table 2: Energy Consumption Figures for Vienna International Airport

Key Energy Consumption Figures of Airport Vienna AG					
	Unit	2017	2018	2019	2020
Traffic units (TU)	[-]	26,496,620	29,238,913	33,716,888	9,343,564
Passengers	[-]	24,392,805	27,037,292	31,662,189	7,812,938
Electricity Consumption	kWh/TU	3.52	3.24	2.72	7.13
Electricity Consumption	MWh	93.358	94,739	91,855	66,583
Heat Consumption	kWh/TU	2.01	1.66	1.46	4.00
Heat Consumption	MWh	53,304	48,591	49,329	37,405
Cooling Consumption	kWh/TU	1.09	1.1	0.92	1.80
Cooling Consumption	MWh	28,846	32,146	30,967	16,812
Fuel Consumption	kWh/TU	1.20	1.15	1.07	1.90
Fuel Consumption	MWh	31,733	33,587	36,093	17,734
Total Energy Consumption	kWh/TU	6.73	6.05	5.26	13.03
Total Energy Consumption	MWh	178,395	176,918	177,277	121,722
Total Energy Consumption	kWh/TU	2.68	3.24	2.72	7.13
Total Energy Consumption	MWh	70,883	94,739	91,855	66,583
Share RES of Total Energy Consumption	%	39.7%	53.5%	51.8%	54.7%

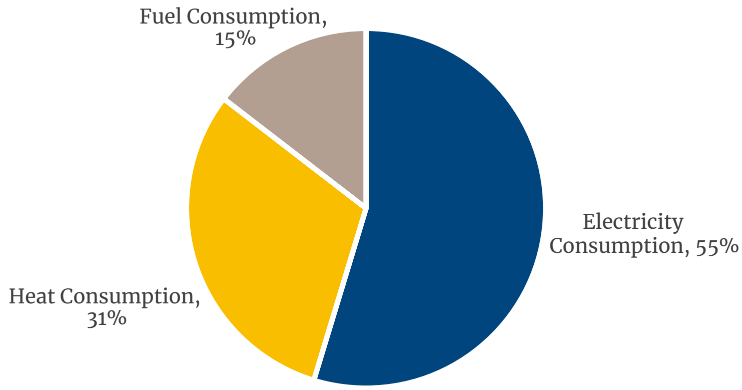
Source: (Flughafen Wien Gruppe, 2020)

[7] https://www.flugplandaten.de/flughaefen-in-europa.htm
[8] For comparison: Average energy consumption per capita in cities 5 – 20 MWh, average 10 MWh would be 1,000 GWh for a city with 100,000 inhabitants.

"Traffic Units" (TU) are defined as either a passenger or 100 kg of air cargo. Specific energy consumption is often shown as energy unit per traffic unit. Figure 2 shows that lower air traffic – due to pandemic restrictions in 2020 – does not lead to a proportional reduction in total energy consumption. For further analysis, we used pre-pandemic figures. Before the pandemic, the average total energy consumption amounted to 170 – 180 GWh, equal to **3 kWh per traffic unit**. In Vienna, more than half of total energy consumption is supplied by renewable sources.

The major share of energy consumption is attributable to electricity. The airport's cooling system is one of the major electricity consumers.

Figure 2: Shares of Total Final Energy Consumption Vienna Airport 2019

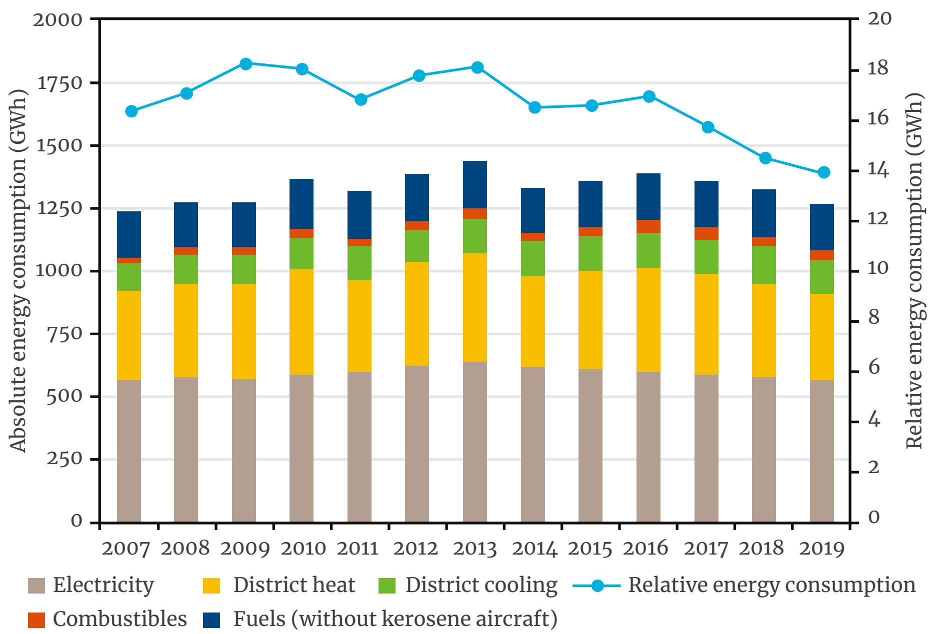


Source: Own chart, based on data from (Flughafen Wien Gruppe, 2020)

In comparison, total energy consumption at Frankfurt Airport is about 10 times higher than in Vienna. Frankfurt's specific energy consumption is about four times higher (around **12 kWh/traffic unit**). In both cases, electricity dominates the energy consumption shares (approx. 50% of final energy consumption).

As a general rule, EPI benchmarking must be treated with caution. Figures can vary significantly and are influenced by several factors. There is no linear relationship between the size of and the energy consumption in airports. Even in the same region, energy consumption shows large variations. For example, in an analysis covering several airports, a study in Greece found their energy consumption ranged between 4 –18 kWh/passenger and 200 – 270 kWh/m² (Sergio Ortega Alba, 2016).

Figure 3: Shares in Total Final Energy Consumption at Frankfurt Airport



Translated from source: (Fraport AG, 2020)

3.2 Energy Consumption Areas in Airports

Generally speaking, energy consumption at airports is strongly affected by the following factors: size of the airport (m^2), outside climate conditions (heating or cooling needs), desired comfort level in the airport, extent of services provided at the airport, operational hours and passenger numbers (Akyüz, Sogüt, & Altuntas, 2017).

Airports are separated into **airside** and **landside areas**. Airside covers the airfield and other buildings, landside the terminal building and parking. Landside related activities and energy consumption must be seen in close connection with passengers and relate to the movement, processing, organisation, and control of passenger, baggage and cargo flows. Typical facilities common to all airports include the terminal building, the cargo building and vehicle parking areas.

Airside refers to everything related to aircraft operation, including landing, take-off and guiding to the apron. Typical airside sub-systems include the control tower, airfield lighting, radio navigation systems, firefighting buildings, hangars and weather facilities (Sergio Ortega Alba, 2016).

Figure 4: Airport Areas

Source: (Sergio Ortega Alba, 2016)

Despite the physical and operational differences in airports, the terminal building is generally the most studied area and the largest energy consumer. For example, the terminal building at Santander Airport accounts for more than 75% of its total energy consumption.

The largest energy consumers are (overall energy consumption share for Santander airport is given in brackets):

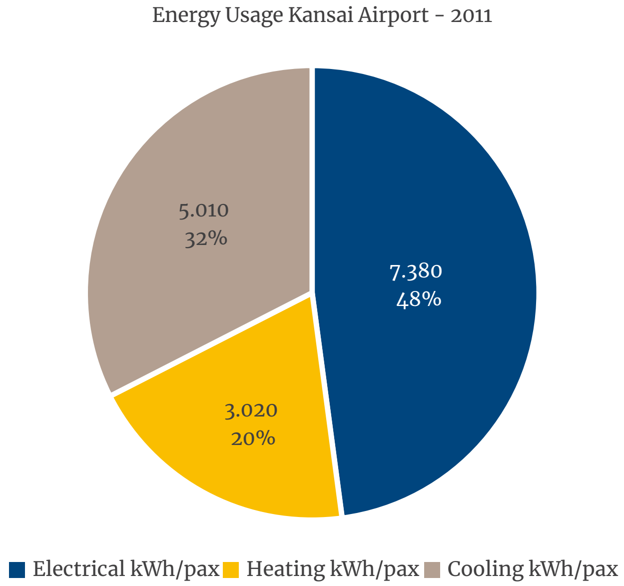
- HVAC systems (24.5 %)
- Lighting (19.8 %)
- External companies (11.8 %)
- Information and communication technologies (18.3 %)
- Airfield lighting (6.9 %)
- Radio navigation systems (4.8 %)
- Electromechanical facilities (2.4 %)
- Others (11.5 %) (Sergio Ortega Alba, 2016)

Energy consumption of external companies like shops and restaurants relates to HVAC and lighting. Accordingly, for airports where energy statistics do not distinguish between airport consumption and that of external companies, the overall HVAC share will be higher. HVAC is the major energy consumer and is addressed in more detail in the next chapter.

3.3 Importance of HVAC Systems

HVAC can contribute to over 50% of an airport's total energy consumption, depending on the climate conditions (Malik, 2017). The following chapter uses the example of Kansai Airport's energy demand to describe a baseline scenario for later energy saving calculations (for cases where improvement measures were not available from literature).

Figure 5: Energy Consumption at Kansai Airport Japan in 2011



Source: Own chart based on (Kansai Airport - Technical Department, 2018)

Some 52% of the total energy consumed at Kansai Airport is used solely for heating and cooling (see Fig. 5). In 2011, major changes to increase energy efficiency had not yet been implemented, so the energy demand resembles an airport in need of improvement. It is for this reason, that **energy consumption and carbon emissions for 2011 have been chosen as the baseline** for calculating the potential energy savings and emission reductions in this report. (Kansai Airport - Technical Department, 2018). The resulting energy requirement per passenger is thus at the upper limit of the ranges cited above (16 kWh/pax).

The corresponding CO_2 emissions per passenger differ from airport to airport. In the example of Kansai Airport, the total emissions are 7.85 kg per passenger; HVAC emissions amount to 4.1 kg per passenger.[9] In comparison, Vienna Airport only emits an average of about 2.85 kg CO_2 per passenger (total emissions).

Temperature and humidity control in terminal buildings poses a unique set of challenges. Since people often arrive in big groups and stay for varying lengths of time, the total energy given off by people to certain spaces constantly varies. Furthermore, as visitors often carry a lot of weight and move around quickly, it

[9] The baseline energy consumption is based on the following energy consumption figures from Kansai Airport:

- Total built up airport buildings: 182,126.00 m²
- Passengers: 12,863,000
- Total energy consumption: 217,532.04 MWh
- Natural Gas consumption: 111,204.00 m³
- Electrical energy consumption: 102,270 MWh
- Cooling: 69,421 MWh
- Heating: 44,729 MWh
- Total CO_2 emissions: 427,000 Tonnes
- CO_2 emissions per passenger: 7.85 kg
- HVAC CO_2 emissions per passenger: 4.10 kg

can be assumed that the heat given off by a person can be between 200 W and 300 W, rather than the usual 80 – 100 W in an office building. The relatively high amount of heat given off per person results in even larger fluctuations in cooling demand.

These factors call for a flexible HVAC system that can respond quickly to the fast-changing cooling and heating loads.

Typical HVAC energy sources are:

- Electricity from the grid
- Fossil fuel for heating or CHP
- Electricity from onsite solar PV
- Onsite geothermal energy

Measures for improving an airport's HVAC system range from simple changes like temperature settings to complex systems like cold and heat storage.

Airports are complex buildings, as touched on in the previous chapter. Because of the complexity and the differing factors, there is no "one size fits all" system that will work for all terminal buildings. However, common measures include:

- Installation of air curtains in boarding bridges
- Adjustment of temperature and humidity levels
- Optimisation of setpoints, e.g. setting AC systems to OFF on weekends or during off peak periods
- Installation of frequency converters on two ventilation systems
- Cold and heat storage (CHS)
- River/ground water cooling
- Combined heat and power (CHP), trigeneration plants (Costa, Keane, & Restoy, 2012)

Some of these measures are relatively simple and are therefore not the subject of further investigation in this paper.

4 Sector Specific Energy Efficiency Measures

The table below provides an overview of selected energy efficiency measures which are presented in detail in the following sub-chapters. Each sub-chapter explains the baseline situation, the measure, and its potential in terms of energy saving and greenhouse gas emission reduction. Due to the scope, the authors focused on the following measures, which were deemed effective and have high replication potential.

Table 3: Energy Efficiency Measures at Airports

Chapter	Measure	Area
4.1	Ground Water Cooling	HVAC
4.2	Using Cold (and Heat) Storages (CHS)	HVAC
4.3	Temperature and Humidity Level Adjustments	HVAC and Energy Management
4.4	Building Analytics Technology	Energy Management
4.5	Sustainability Rating Systems	Energy Management
4.6	Electrification of Ground Support Equipment	Transportation
4.7	Efficient Baggage Handling System	Transportation
4.8	Central Utility Plant (Cogeneration, Trigeneration)	Energy Supply
4.9	Photovoltaic & Storage	Energy Supply (Renewable Energy)
4.10	Building Envelope	Architecture
4.11	Potential Savings through Architectural Design Choices	Architecture

4.1 Ground Water Cooling

4.1.1 Baseline Situation and Energy Consumption

To ensure thermal comfort, maintaining a stable indoor temperature and air quality within an airport typically represents the single most significant contribution to energy usage.

However, in terms of coefficient of performance (COP), conventional compressor chillers are now outperformed by ground water cooling systems. These utilize the stable temperature level in the ground water, thereby making for more constant operational conditions. COP is defined as the relationship between the power that is drawn out of the cooling system, and the power that is supplied to the compressor.

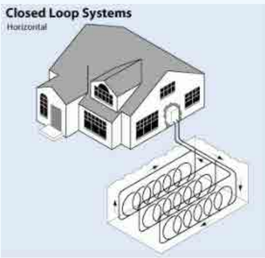
4.1.2 Suggested Measures for Improvement

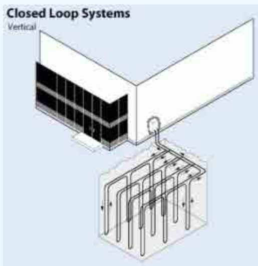
This section evaluates the best practice for implementing cooling technologies in buildings utilizing water as a natural source for cooling.

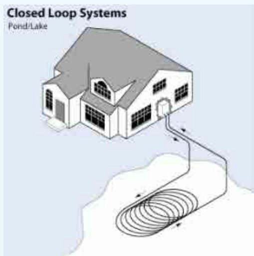
The usual cooling method using ground water is based on the employment of heat pumps in conjunction with open or closed geothermal loops. The design of the geothermal loop systems depends on various factors such as climate, soil conditions, available land and ground water sources, and local installation costs (Sarbu & Sebarchievici, 2015).

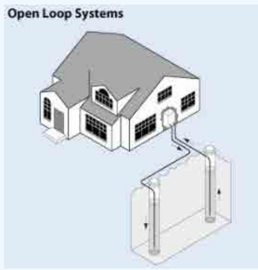
There are four basic types of ground (water) cooling systems, as depicted below. Three of these – horizontal, vertical, and pond/lake – are closed-loop systems. The fourth is the open loop system.

Figure 6: Principal System Designs for Groundwater Cooling









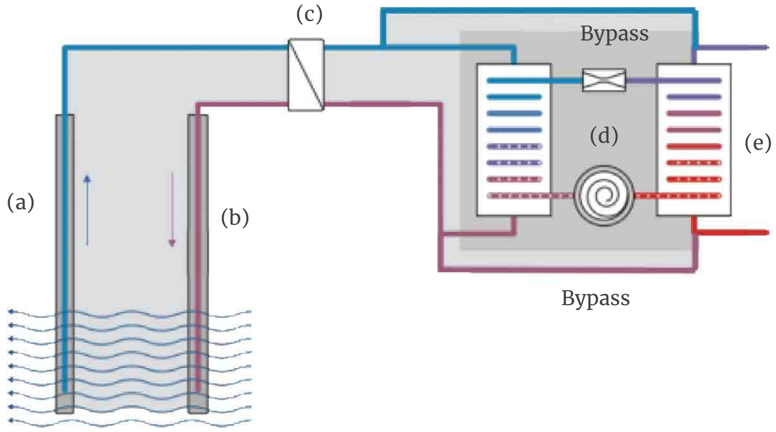
Horizontal	Vertical	Lake/River	Vertical
Closed Loop System			Open Loop System

Source: greenmanual.rutgers.edu/nr-geothermal-heat-pumps/

Closed loop systems differ from open loop systems only in that they include a geothermal loop. An open system pipes ground water directly to a heat pump before feeding it back into the ground, rather than circulating a coolant in a closed underground heat sink.

In general, ground water cooling with an open loop system requires the following components (see Fig. 7):
(a) Production well (cold well) to extract groundwater
(b) Injection well (warm well) for reinjecting the used groundwater into the groundwater body
(c) Ground heat exchanger (GHE) to separate the primary circuit (groundwater) from the secondary circuit (cooling system of the building)
(d) Heat pump for shifting the temperature level between the primary and secondary circuits
(e) A short-term technical heat storage to buffer peak loads

Figure 7: Open loop system



Source: Adapted from (Viessmann, 2022)

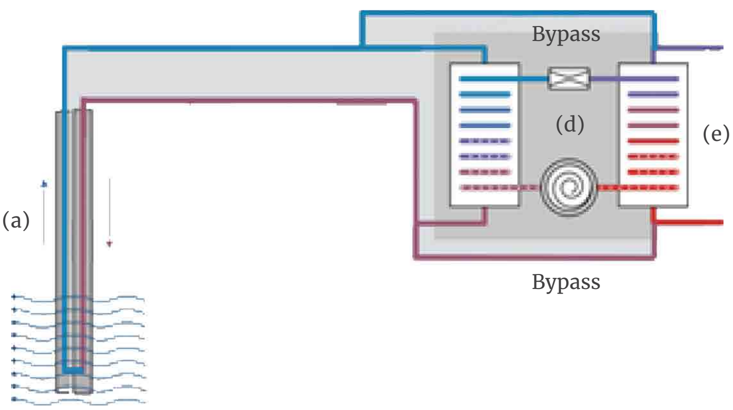
Open loop systems inject groundwater from a well to cool down a medium in the building or in a reversed heat pump process to leverage the thermal coolant energy. In most cases, the temperature level is sufficient for direct cooling without the use of a heat pump. However, heat pumps can also be utilised for active cooling.

One specific type of open loop system design involves aquifer thermal energy storage (ATES). ATES is a bidirectional system which uses at least one groundwater well to actively store excess heat in summer and cooling capacity in winter. ATES is a suitable technique for use in supplying airport buildings with large amounts of heating and cooling.

Where the water of the heat sink is of poor quality, it is recommended that the heat exchanger be installed inside the underground reservoir in a closed loop system. In the **closed loop systems**, the heat carrier fluid is circulated in an array of pipes inserted in the ground. The heat carrier fluid is usually water or water mixed with an anti-freeze liquid, and can be used as the cooling medium in the building itself (Sarbu & Sebarchievici, 2015). In the figure below, the array of pipes is symbolised by one vertical loop.

Figure 8 shows the various components: (a) Vertical loop, (d) heat pump for shifting the temperature level between the primary and secondary circuits, and (e) a short-term technical heat storage to buffer peak loads.

Figure 8: Closed loop system



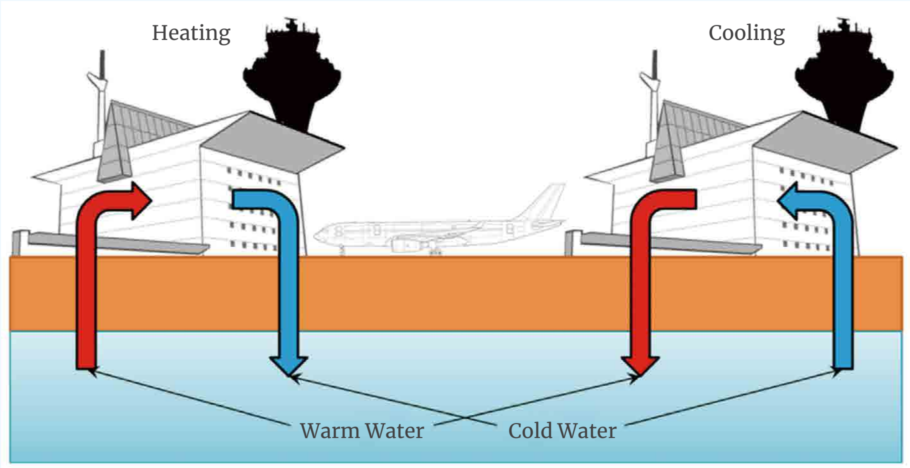
Source: Adapted from (Viessmann, 2022)

ATES at Copenhagen Airport

Copenhagen Airport adopted the aquifer thermal energy storage (ATES) (groundwater cooling) system for cooling. Its principal function is to provide comfort cooling at the airport, with heating as a secondary function. The system produces cooling with a coefficient of performance (COP) of 60. This means that for each kWh consumed, the system delivers 60 kWh of cooling. Since 2015, after the airport completed the final phase of the production side of the groundwater cooling system, it was able to supply approximately 4 million kWh of cooling annually.

Figure 9 shows the principle behind the ATES used at Copenhagen Airport, heating the airport in winter by pumping water in from the warmer half of the dipole (left) and cooling in summer by pumping water in from the cooler half (right). The buildings in the picture show the same building in winter (left) and summer (right).

Figure 9: ATES at Copenhagen Airport



Source: (Baxter, Srisaeng, & Wild, 2018)

4.1.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

An open or closed groundwater-source system using heat pumps can produce three to four times more heating or cooling energy than it consumes in electrical energy (for water pumps). If a system can be run to provide cooling via a simple heat exchanger, without using a heat pump, overall efficiency is greatly increased, and the ratio of cooling energy delivered to electrical energy consumed can exceed 20 – 60. This means that for each kWh consumed, the system delivers up to 60 kWh of cooling (Baxter, Srisaeng, & Wild, 2018).

Investment costs for the open loop system (ATES) shown range between €580/KW and €1,000/kW (Schüppler, Fleuchaus, & Blum, 2019).

Table 4: Key Facts of Measure – Ground Water Cooling

Key Facts of Measure – Ground Water Cooling	
Investment Cost:	€580/KW – €1,000/kW (for an open loop system, example ATES)
Energy Savings: (thermal)	-
Energy Savings: (electrical)	80% for cooling (open loop system) without reversed heat hump (HP) compared to standard chillers 20% – 30 % with HP and any geothermal loop system
CO_2 mitigation:	Up to 650 tCO_2/MW cooling capacity
Benefits:	• High electricity savings • Short payback time possible <2.7 years • Low maintenance costs • Scalable and suitable for large cooling loads • Can be used for heating and cooling
Disadvantage:	• Higher capital costs compared to standard chillers

4.2 Adjusting Temperature and Humidity Levels

4.2.1 Baseline Situation and Energy Consumption

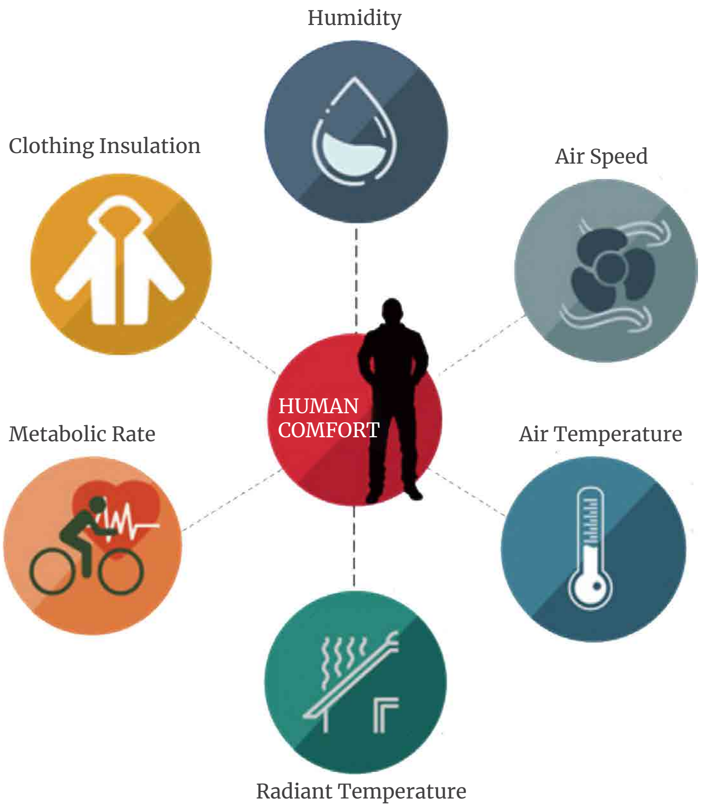
Most airport terminals are characterised by open, large spaced halls with non-uniform heat distribution due to extensive glazed façades. Besides that, a range of different and alternating occupancy activities contributes to these non-uniformities. As a result, HVAC systems use large amounts of energy to respond quickly to provide overall **thermal comfort conditions** in airport buildings.

4.2.2 Suggested Measures of Improvement

Beside other efficiency measures, it is well reported that a reduction in energy used for regulating the indoor thermal environment can be achieved by optimising indoor environmental controls.

Thermal comfort as such is a broad concept. It is not determined by a single factor, but by a subjective feeling produced by the human body in response to a wide range of environmental and personal indicators. These indicators are illustrated in Figure 10. Environmental indicators characterise thermal environment conditions (i.e., air temperature, air speed, humidity), whereas personal indicators are described by the metabolic rate (physical work we do) and type of body insulation (effect of clothing on the wearer).

Figure 10: Indicators of Thermal Comfort



Source: (Kumar, 2019)

Based on these indicators, different control concepts can be used to assess the best-fitting thermal comfort conditions for a given environment.

According to studies on and field surveys of both passengers and staff at different airports in the UK, it was found that the acceptable temperature range in winter is 19.2 – 23.1 ºC and 23.9 – 27.3 ºC in summer. This compares with ASHARE's[10] design criteria which recommends a temperature of 23 – 26 ºC and a relative humidity range of 30% – 40% in winter and 40 – 55 % in summer. In addition, air circulation in an airport terminal should be within the range of 0.1 – 0.2 m/s, aiming for an 80% acceptability comfort zone.[11]

However, some places – such as arrival halls and gates – may exceed this range and reach up to 0.3 m/s. Also, personal factors such as clothing insulation and metabolic rate should be taken into account when determining indoor environmental conditions. The table below shows the recommended comfort criteria for airport terminal spaces and indoor environmental conditions collected from field surveys conducted at different airports. The recommended temperature depends on the season (due to different clothing in summer and winter) and on the activity level (lowest in the lounge, highest at baggage reclaim) as summarised below.

Table 5: Recommended Comfort Criteria for Airport Terminal Spaces

	Summer[a]	Winter[a]	Activity (met)
	Operative temperature (℃)		
Baggage reclaim	21-25[b]	12-19[b]	1.8
Check-in areas[c]	21-23	18-20	1.4
Concourse (on seats)	21-25[b]	19-24[b]	1.8
Customs area	21-23	18-20	1.4
Departure lounge	22-24	19-21	1.3

[a] For clothing insulation of 0.65 clo in summer and 1.15 clo in winter.
[b] Based on PWV of ±0.5. At other cases based on PMV of ±0.25.
[c] Based on comfort requirements of check-in staff.

Source: (Kotopouleas & Nikolopoulou, 2016

Based on the recommendations shown above, many cases can be studied using software tools for environmental controls and parameters can be studied to achieve the optimum solution for optimum operating conditions and with implications for energy saving strategies (Kotopouleas & Nikolopoulou, Thermal comfort conditions in airport terminals: Indoor or transition spaces?, 2016).

A different study investigates an adaptive model to control the supply air conditions at predefined thermal comfort levels based on data-driven and learning algorithms. It was found that the model achieves significantly improved comfort levels about 14% more efficient than comparison models based on ordinary time schedule or flight schedule control strategies (Kapil, Nusrat, & Elangovan, 2019).

[10] The American Society of Heating, Refrigerating and Air-Conditioning Engineers is an American professional association seeking to advance heating, ventilation, air conditioning and refrigeration (HVAC&R) systems design and construction.
[11] Due to different personal perception of comfort, a state is deemed acceptable if 80% of people are satisfied with the prevalent conditions.

4.2.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Measures to adjust temperature and humidity can save up to 20% of energy and CO_2 and improve not only efficiency, but also thermal comfort.

Table 6: Key Facts of Measure – Adjusting Temperature and Humidity Levels

Key Facts of Measure – Adjusting Temperature and Humidity	
Investment Cost:	Approximately €0.2/m² annual costs (software and manpower)
Energy Savings: (thermal)	Up to 20% for heating energy
Energy Savings: (electrical)	Up to 20% for cooling energy
CO_2 mitigation:	Up to 20% of baseline HVAC-related CO_2 emissions
Benefits:	• Easy implementation of pre-defined setpoints • Improves thermal comfort and overall efficiency
Disadvantage:	• Time consuming data collection and preprocessing for implementing advanced environmental controls

4.3 Cold and Heat Storages (CHS)

4.3.1 Baseline Situation and Energy Consumption

The energy consumption of the HVAC system in terminal buildings is substantial. Up to or above 50% of the total landside energy consumption can be attributed to the HVAC, depending on various factors.

The CO_2 emissions per passenger amount to about 4.1 kg for HVAC alone. Depending on the climate, usually cooling causes the highest energy consumption and therefore the highest emissions.

Usually, airports have either a centralised or a decentralised heating and cooling system. Cooling is done by feeding cool air into indoor spaces that require energy to be transported away in order to maintain the desired temperature. Heating is provided by supplying hot water or steam to the areas that require energy in order to maintain the desired temperature. Normally, the heat from the spaces that are being cooled is released to the air outside the airport building via heat exchangers and fan coils, whereas the energy required to heat up spaces is produced from electricity or burning of fuel.

4.3.2 Suggested Measures of Improvement

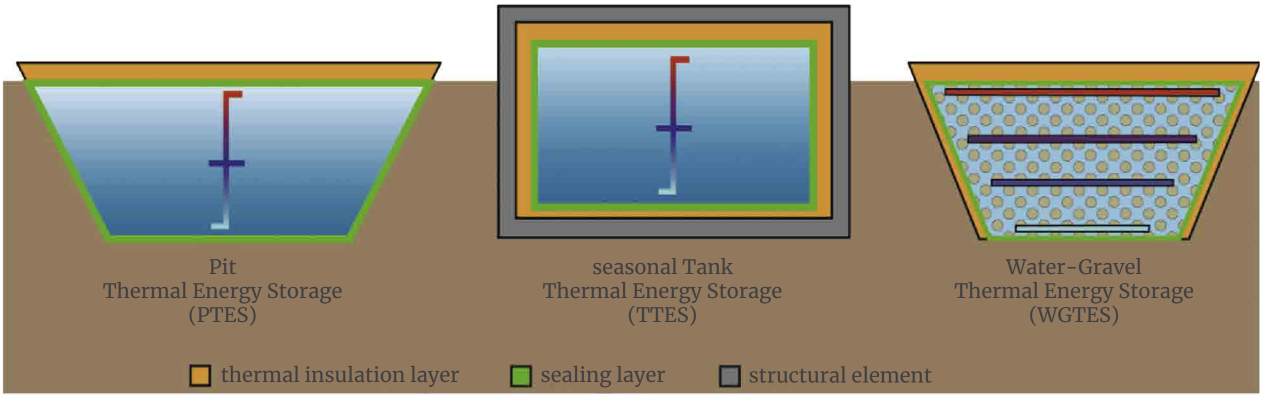
Seasonal energy storage offers a solution to reduce the amount of energy required for heating and cooling. There are various forms of CHS, which can be split in two categories: above ground/surface and below surface CHS. The core principle is to transfer heat from buildings to storage in summer and then use it to heat buildings in winter. Usually, this includes using a heat pump to increase efficiency. The storage medium is often water, but can also be soil.

For systems that operate at higher temperatures, molten material can be used that can be heated well beyond 1,000 °C (The Engineer, 2016).

Ground level storage typically consists of heat exchangers and a storage pit that is filled with water and potentially gravel as depicted in Figure 11. Tank thermal energy storage (TTES) will retain heat to a higher degree, but also involves more complex construction and is therefore more expensive. Pit thermal energy storage (PTES) is the simplest construction, but will also have the highest heat losses to the surrounding soil. Water-gravel thermal energy storage (WGTES) is slightly superior in terms of heat retention, but the main advantage is the layering of the water. Because of the gravel, the water moves more slowly and therefore cooler water at the bottom will mix less with the warm water at the top. This is beneficial in the process of heat exchanging from the WGTES to the HVAC system.

Currently, the largest project in the world to use this technology is seen in Denmark (Vojens). It consists of 210,000 m^3 of storage and has a storage capacity of 12,180 MWh, showcasing the technology's potential. It can charge or discharge with a capacity of 38,500 kW. The investment cost for this project was just €0.41/kWh (Solar Thermal World, 2022).

Figure 11: Ground Level Storage Methods for Cold and Heat Storage

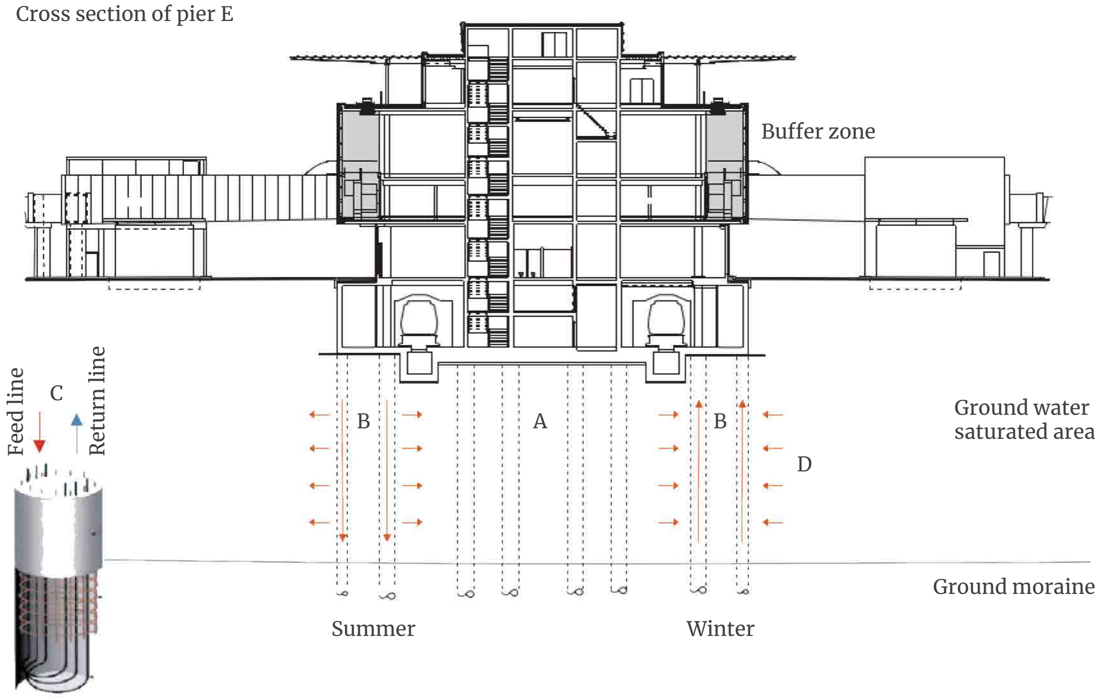


Source: (Bott, Dressel, & Bayer, 2019

Almost all of the **underground storage systems** share the same core principle. Heat is extracted from the building during summer and given off to storage underground. That storage can either be created specifically for the purpose, for example by flooding a cave, or can be natural; the simplest form being the soil under the building.

One such example was built at Zurich Airport. Due to the instable soil, the pier had to be constructed on 441 piles (see: (A) in the chart below). Of these piles, approximately 310 were equipped as 'energy piles', reaching 30 m into the ground moraine (B). A water-glycol mixture is pumped through tubes integrated into the concrete piles (C) in order to exchange heat with the surrounding soil. This heat exchanger is used in conjunction with the ground water-saturated soil (D) as a form of seasonal storage. During the summer, internal excess heat is collected via a heat exchange and ventilation system and is stored in the soil via the energy piles. The necessary cooling that is required for heat exchange can be provided almost entirely by the energy piles. In winter, the demand for heating can be covered by internal excess heat and heat from soil storage. A heat pump is used as part of this process. In total, about two-thirds of the cooling and heating demand can be covered by the system (Flughafen Zürich AG, 2012).

Figure 12: CHS at Zürich Airport



Source: (Flughafen Zürich AG, 2012)

Since the piles had been necessary because of the soil, the CHS in this instance only required pipes (to be integrated into the piles), the heat pump and the water-glycol mixture.

Choosing the optimal storage method depends on the climate conditions, along with other factors. Therefore, the planning phase must be well thought through in order to reap the benefits of this improvement measure.

4.3.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

The energy savings for cooling can be as much as 80%,[12] while the energy savings for heating can amount to 30%[13] for groundwater-based storage. In total, savings of about two-thirds of the total energy required for heating and cooling can be achieved (Snijders).

CHS can result in emissions savings as high as 1.5 kg/passenger (Flughafen Zürich AG, 2012). It is most suited for central climate areas and least suited in the coldest areas, as the savings of energy required for cooling are much higher than the savings for heating.

Table 7: Key Facts of Measure – Cold and Heat Storage

Key Facts of Measure – Cold and Heat Storage	
Investment Cost:	Largely depending on the specific situation Pit storage for example €0.4/kWh – €0.6/kWh
Energy Savings: (thermal)	Up to 30% (heating)
Energy Savings: (electrical)	Up to 80% (cooling)
CO_2 mitigation:	Up to 2.8 kg per passenger
Benefits:	• Large savings in electrical and thermal energy • Pairs well with technologies that produce excess heat (e.g. Solar thermal, CHP) • Scalability
Disadvantages:	• Not all technologies can be retrofitted • Depending on the system, thermal pits in particular may suffer considerable heat loss • Not suitable for cold areas

[12] Replacing less efficient electricity-powered standard chillers
[13] Replacing thermal energy supplied from conventional sources

4.4 Building Analytics Technology

4.4.1 Description of Baseline Situation and Energy Consumption

Most commercial buildings already use building management systems (BMS) to manage the daily operations of a facility. While BMS provides features like alerts, notifications and metering dashboards, energy management and information systems (EMIS) and related software platforms go one step further, utilising comprehensive data analysis tools with intelligent control algorithms.

In contrast to BMS, EMIS comprise a broad set of tools and services to manage building energy use. These technologies offer a mix of capabilities to store, display, and analyse energy use and system data, and once implemented can enable control of HVAC systems, lighting, and other relevant utilities at airports (Lin, Singla, & Granderson, 2017).

The baseline for this measure is an airport with no advanced building analytics systems installed.

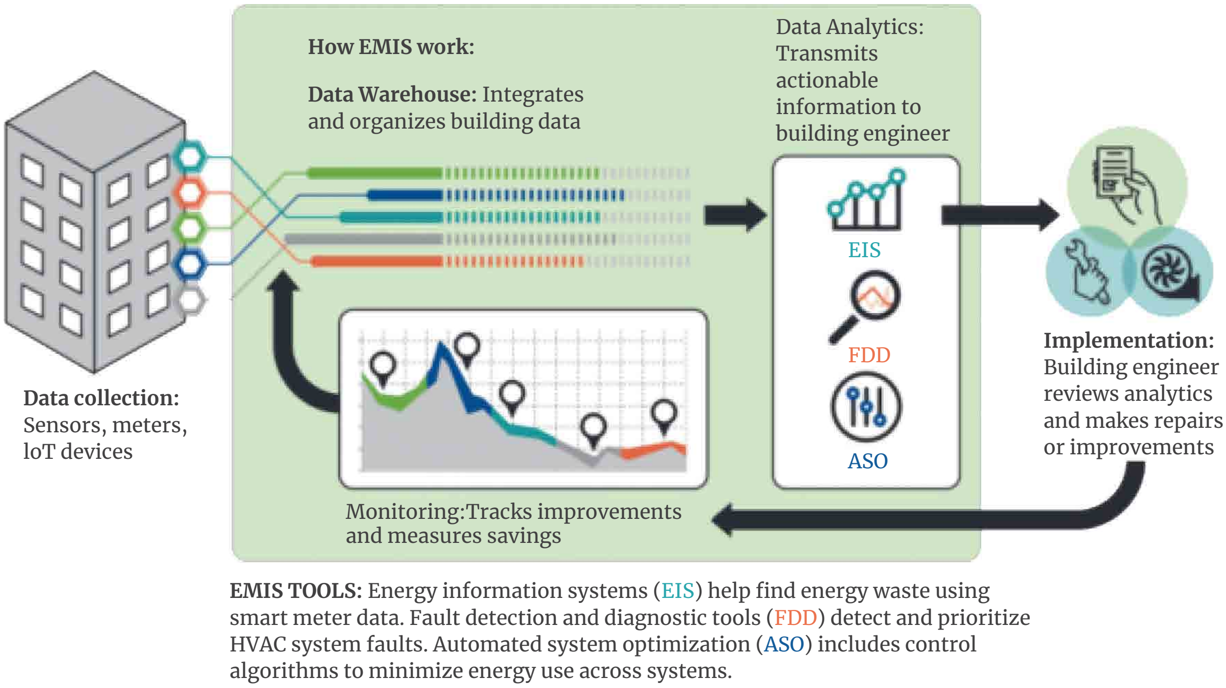
4.4.2 Suggested Measures of Improvement

All data generated using EMIS tools are designed to operate buildings more efficiently while increasing occupants' comfort. This is done by providing visibility into and analysis of the energy-consuming utilities. EMIS tools are usually used in the monitoring-based commissioning (MBCx) process. The MBCx process is defined as the implementation of an ongoing commissioning process with focus on monitoring and analysing large amounts of data on a continuous basis. The components and how they interact are shown in Figure 13.

Generally speaking, in smart energy analytics there are three major software subsets of EMIS technologies:

- An **energy information system (EIS)** is broadly defined as software, data acquisition hardware, and communication systems used to store, analyse, and display building energy data. EIS are a subset of EMIS focused on meter-level monitoring (hourly or more frequent).
- **Fault detection and diagnostics (FDD)** is a software tool used to automate the process of detecting faults in physical building systems and processes and help diagnose their potential causes. FDD are a subset of EMIS, focused on system-level monitoring using building automation system (BAS) data.
- **Automated system optimisation software (ASO)** continuously analyses and modifies BAS control settings for HVAC system energy usage while maintaining occupant comfort. These tools both read data from the BAS and automatically send optimal setpoints back to the BAS to adjust the control parameters, based on data such as logged energy use and the energy price signal (Kramer, Lin, Curtin, Crowe, & Granderson, 2020).

Figure 13: Monitoring-Based Commissioning Process



Source: (Kramer, Lin, Curtin, Crowe, & Granderson, 2020)

The table below summarises the applications available by EIS, FDD or ASO technologies, as well as commonly associated analysis approaches and data requirements.

Table 8: Summary of Applications for EIS, FDD and ASO Technologies

Applications	Applicable EMIS Type	Analysis Approach	Common Data Requirements
Scheduling	EIS	Load profiling	Whole-building or sub metered energy use
		Base-to-peak load ratios	
		Heat maps	
	FDD	Tool dependent	System and equipment status: air-handling units HVAC terminal units, cooling towers, chillers, boilers; fans, pumps
Simultaneous heating and cooling	EIS	Energy signature	Outdoor air temperature, whole-building or sub-metered energy use
	FDD	Tool dependent	Outdoor air temperature HVAC: heating, preheating, and cooling coil valve status; outdoor air damper position Terminal units: reheat coil valve status
Outdoor air usage	FDD	Tool dependent	Outdoor air temperature HVAC: mixed-air temperature, discharge air temperature and setpoints, return air temperature, outdoor air damper position
Air-side setpoint optimisation			HVAC: discharge air temperature and setpoint, static pressure and setpoints, zone heating and cooling temperature and setpoints
Sensor errors			Outdoor air temperature HVAC: discharge, return air, and mixed air temperature; wet bulb temperature or relative humidity Zone: thermostat space temperature, carbon dioxide Central plant: hot water, chilled water, and cooling tower condenser water leaving temperatures
Portfolio prioritisation	EIS/ASO	Cross-sectional benchmarking	Gross floor area, whole-building or sub-metered energy use
Automated savings estimation		Avoided energy use or energy cost	Outdoor air temperature Continuous whole-building or sub-metered energy use
Continuous energy anomaly detection		Typical use vs. actual use	
Peak load management		Load profiling and load duration curves	Whole-building electricity demand, pass

Source: (Kramer, Lin, Curtin, Crowe, & Granderson, 2020)

4.4.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Research indicates that 5% – 30 % of whole-building energy consumption is attributable to faulty or degraded operations, some of which is identifiable with FDD tools (Kramer, Lin, Curtin, Crowe, & Granderson, 2020). Thus, we assume that, realistically, up to 20% of energy can be saved by using building analytics technology – depending on the actual state of the building in question.

Case Study I: Adelaide Airport, Australia[14]
Adelaide Airport uses advanced building analytics to address complex internal heating, ventilation and air conditioning system inefficiencies. With the deployed EMSI system, the airport is on track to savings of 600 tCO_2e and 933 MWh a year, with a payback period of only seven months. The system will continue to improve the emission savings potential through advanced controls algorithm like machine learning, as well as improving the lifecycle of equipment.

Case Study II: CASCADE Rome-Fiumicino and Milan-Malpensa[15]
The project conducted in the Rome-Fiumicino and Milan-Malpensa airports has pinpointed an innovative solution that incorporates existing building automation/building management systems (BAS/BMS) with an automated FDD system for HVAC linked to an ISO 50001-based Energy Action Plan. The solution has identified large energy savings potential of up to 20% at both airports. For Terminal 1 at Fiumicino Airport, this amounts to 363 MWh electricity, 691 MWh heat and 527 MWh chilled water savings per year or about €90 k/y and 230 tons of CO_2.

Table 9: Key Facts of Measure – Building Analytics

Key Facts of Measure – Building Analytics Technology	
Investment Cost:	Annual cost: €1.4/m² (base cost + annual labour cost; median, (Kramer, Lin, Curtin, Crowe, & Granderson, 2020))
Energy Savings: (thermal)	20%
Energy Savings: (electrical)	20%
CO_2 mitigation:	20%
Benefits:	• Reflect the energy efficiency of key energy-using systems and equipment • Strengthen communication and training to raise employees' awareness of the need for energy conservation • Integration with different environmental management systems possible (ISO14000, ISO 50001) • Improved occupant comfort
Disadvantages:	• Limited information on the true costs and potential savings from using varying degrees of analytics • Problems integrating data into the EMIS • Lack of clarity on differences between EMIS products • Lack of existing metering in place

[14] Source: https://www.adelaideairport.com.au/corporate/wp-content/uploads/2020/06/090-NJ01311_MP_Final_-Digital_FA.pdf ,
[15] Source: https://ec.europa.eu/programmes/horizon2020/en/news/cascade-reducing-energy-use-airports

4.5 Sustainability Rating Systems

4.5.1 Baseline Situation and Energy Consumption

The baseline for this measure is an airport with no sustainability rating systems installed.

4.5.2 Suggested Measures of Improvement

Apart from established energy management systems (ISO 50001) and environmental management systems (ISO 14001), a variety of internationally accepted sustainability rating systems exist. They mostly address buildings, building complexes, industries and in some cases cities. This section briefly describes some of the major sustainability systems in use.

These concepts include energy-related and GHG-relevant topics, but often go much further (see table below). For airports, Airport Carbon Accreditation – a global standard for carbon management at airports – applies. Overall responsibility lies with the Airports Council International (ACI).[16] An independent programme administrator guides airports through the application process. The benefits from accreditation range from a better understanding of airport emissions to the achievement of quantified emission reductions, facilitation of best practice exchange and enhanced publicly-perceived credibility of climate action by the airport industry (Airports Council International, 2021).

As is typical in carbon footprint analysis, emissions of all three scopes (airport-controlled sources, purchased electricity and other sources related to airport activities) are taken into account (see Figure 14).

[16] https://www.aci-europe.org/industry-topics/industry-topics/28-airport-sustainability.html

Table 10: Overview of Sustainability Rating Systems

Sustainability Rating System / Homepage	Rating Categories	Major Rating Sections	Assessment	Example
BREEAM Building Research Establishment's (BRE) Environmental Assessment Method. http://www.breeam.org)	• Outstanding (top 1% non-residential buildings) • excellent (best practice of top 10% buildings) • very good (advanced good practice, top 20% of UK buildings) • good (top 50%) • pass (top 75%, standard good practice) • unclassified	Energy, Materials, Health & Wellbeing, Management, Land Use & Ecology, Pollution, innovation, Transport and Water	By licenced assessors following a quality assessment	"Excellent" rating for Oslo Airport https://avinor.no/en/corporate/airport/oslo/development/this-is-new/miljovennlige-valg Specific measures taken comprise the installation of wooden roof instead of metallic, use of passive standard building, expansion of railway station to increase public transport, and use of sewage and snow as energy sources. [17]
LEED Leadership in Energy & Environmental Design https://www.usgbc.org/leed	• Platinum • Gold • Silver • Certified	Energy & Atmosphere, Sustainable Sites, Indoor Environmental Quality, Materials & Resources etc.	Certificates are issued by the Green Building Certification Institute	Several airports in the US, such as Hartsfield-Jackson Atlanta International Airport, Nashville International Airport and Seattle-Tacoma International Airport (https://www.usgbc.org/articles/leed-certified-airports-help-provide-safe-and-sustainable-travel).
Green Mark launched by the Singapore's Building Construction Authority (BCA) https://www.mnd.gov.sg/our-work/greening-our-home/bca-green-mark	• Based on the Code for Environmental Sustainability of Buildings • Gold • GoldPlus • Platinum	Energy Efficiency (weighing 61%), followed by Environmental Protection	Process between BCA and development team	---

[17] Sewage from the northern parts of Ullensaker, Nannestad and Oslo Airport will be recovered and used for heating. Snow from the past winter will be used to cool the North Pier. The airport has its own district heating system where district heating is produced using environmentally friendly heat pump technology

Sustainability Rating System / Homepage	Rating Categories	Major Rating Sections	Assessment	Example
BEAM Plus Building Environmental Assessment Method https://www.hkgbc.org.hk/eng/beam-plus/beam-plus-new-buildings/index.jsp	• Bronze • Silver • Gold • Platinum • (Different schemes for new, existing buildings and interior)	Energy use, site aspects and indoor environmental quality	By independent assessors and BEAM Society Limited	Airports are classified as special buildings (with restricted access) and can follow a specific guide. (https://www.hkgbc.org.hk/eng/news-events/news/2016/20160930.jsp).
Energy Star Established by the US Environmental Protection Agency https://www.energystar.gov/	• Product and building ratings • Commercial buildings reaching a score of 75 or higher	---	Energy Star Portfolio Manager	This rating is dedicated to specific buildings rather than to large complexes like airports. Examples from airports comprise specific buildings or hotels in the area. https://www.energystar.gov/buildings/reference/find-energy-star-certified-buildings-and-plants/registry-energy-star-certified-buildings
Airport Carbon Accreditation Overall responsibility is with the Airports Council International (ACI). https://www.aci-europe.org/industry-topics/industry-topics/28-airport-sustainability.html	Six levels of accreditation with different levels of ambition exist	Level 1 Mapping: Policy commitment to emission reduction by top management, development of carbon footprint incl. Scope 1 and 2 Level 2 Reduction: Plus formulation of carbon emission reduction target, development of Carbon Management Plan to achieve targets Level 3 Optimisation: Plus Carbon Footprint incl. Scope 3, formulation of Stakeholder Engagement Plan Level 3+: Level 3 and offsetting remaining emissions Level 4 Transformation: Plus policy commitment to absolute savings, more extensive footprint and Carbon Management Plan, development of Stakeholder Partnership Plan	An independent programme administrator	Level 1: Phuket International Airport Level 2: Bahrain International Airport Level 3: Shenzhen Bao'an International Airport Level 3+: Rajiv Gandhi Airport Level 4: Christchurch Airport

Source: Own table based on data from: (Airports Council International, 2021) and (Ove Arup & Partners Ltd., 2014)

The following chart summarises typical emission sources at airports.

Figure 14: Emission Sources at Airports

Source: (Airports Council International, 2021)

Airport Carbon Accredited: San Francisco International Airport

With about 57 million passengers per year, San Francisco International Airport has reached Level 3 (optimisation). Its main initiatives towards increased sustainability included three major projects. First, they put into operation six fully-electric buses of the type Proterra Catalyst E2, which can be charged in less than 4.5 hours. Annual savings due to lower fuel prices and maintenance costs are estimated at USD 4.5 million and savings of more than 10,500 tonnes. Second, the Fitwel-Certified[18] Harvey Milk Terminal 1 uses only one-third of the energy of its predecessor due to a tote-based baggage system, dynamic glazing, radiant HVAC and regenerative moving walkways. Thirdly, the airport conducted a zero-emission vehicles readiness study and its work on the topic continues (Airports Council International, 2021).

[18] Fitwel is the world's leading certification system committed to building health for all®

4.5.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Unlike other specific energy/GHG saving measures, implementation of sustainability systems per se does not lead to direct savings. However, comprehensive, structured and regular analysis of processes leads to continuous improvements. Depending on the specific requirements of the programmes involved, pre-defined targets need to be achieved in order to be awarded a specific certificate.

Table 11: Key Facts of Measure – Sustainability Rating Systems

Key Facts of Measure – Sustainability Rating Systems	
Investment Cost:	Depending on System and Size of Building, approx. €16,000
Energy Savings: (thermal)	N/A (assumption 10-20%)
Energy Savings: (electrical)	N/A (assumption 10-20%)
CO_2 mitigation:	N/A (assumption 10-20%)
Benefits:	• Comprehensive analysis of various aspects of energy and resource efficiency • Incentive for improvements in subsequent upgrades • Clearly visible ratings
Disadvantages:	• Effort of implementation

4.6 Electrification of Ground Support Equipment (Baggage and Passenger Transport)

4.6.1 Description of Baseline Situation and Energy Consumption

Ground support equipment (GSE) refers to the support equipment used at an airport, usually on the apron,[19] which is used to service the aircraft whilst on the ground. It generally involves ground power operations, aircraft mobility, and cargo/passenger loading operations (Wikipedia, 2022).

Ground support equipment (GSE) is the term for all equipment and vehicles responsible for transporting baggage and passengers and for taxiing aircraft and refuelling. Major airports operate up to several hundred types of airside ground support equipment (GSE) and vehicles (AECOM, 2020).

Apart from non-powered GSE equipment (dollies, chocks, aircraft tripod jacks and aircraft service stairs), the **following types of GSE** exist:

- Refuelers: self-contained fuel truck or a hydrant truck or cart
- **Tugs and tractors**: used to move all equipment that cannot move itself, including bag carts, mobile air conditioning units, air starters, and lavatory carts
- Ground power units: vehicles capable of supplying power to aircraft parked on the ground
- **Buses**: used to move people from one terminal to another or to the plane
- Container loader: also known as cargo loaders or "K loaders", used for loading and unloading of containers and pallets onto and out of aircraft
- Transporters: cargo platforms to load and unload containers and transport cargo
- Air start unit: device used to start an aircraft'' engines
- Non-potable water trucks
- Lavatory service vehicles
- Catering vehicle
- Belt loaders: vehicles with conveyor belts for unloading and loading baggage and cargo onto aircraft
- Passenger boarding steps/stairs
- Pushback tugs and tractors: used to push an aircraft away from the gate when it is ready to depart. These tugs are very powerful and because of the large engines, are sometimes referred to as an engine with wheels. Pushback tugs can also be used to pull aircraft in various situations, such as to a hangar
- Vehicle de/anti-icing equipment
- Aircraft rescue and firefighting equipment (Wikipedia, 2022)

Buses, tugs and tractors are explicitly addressed in this chapter as they are used at almost all airports.

Typically, GSE use diesel or petrol fuels, which collectively contribute to a significant share of airport emissions, including carbon dioxide (CO_2), nitrogen oxides (NO_X), sulphur oxides (SO_X) and particulates (AECOM, 2020).

As an example, typical fuel consumption of diesel-fuelled buses at zero slope is given below.

[19] The airport apron, apron, flight line, ramp, or tarmac is the area of an airport where aircraft are parked, unloaded or loaded, refuelled, boarded, or maintained. (definition Wikipedia)

Table 12: Fuel Consumption in Diesel Buses

Bus type	Area	Traffic flow			Average in Germany
		free flow	dense	Stop & go	
		l/100 km	l/100 km	l/100 km	l/100 km
Bus <15 t gross vehicle weight (e.g. midi-bus)	City	21.8	30.6	39.2	29.9
	Overland	23.0	23.5	34.1	23.0
	Average	22.8	30.2	38.7	27.2
Bus >15-18 t gross vehicle weight (e.g. standard bus)	City	28.7	43.1	55.6	42.0
	Overland	29.3	31.3	48.1	29.5
	Average	29.2	42.5	54.9	37.0
Bus >18 t gross vehicle weight (e.g. jointed bus)	City	36.3	54.0	60.8	52.5
	Overland	37.5	41.0	56.5	37.8
	Average	37.3	53.3	60.4	46.6

Source: Translated from (Schmied & Mottschall, 2014)

Thus, for average-sized buses with no traffic, but only very short distances at airports, we can assume values of around 40 l/100 km or 400 kWh/100 km.

4.6.2 Suggested Measures of Improvement

Fossil-fuelled GSE technologies could be replaced by electric GSE (eGSE). These offer a cleaner alternative to using combustible fuels and can reduce emissions by up to 100% when powered by renewables. The actual GHG emission reduction depends on the actual electricity mix (including solar PV and battery energy storage; renewable electricity from the grid or energy-from-waste) (AECOM, 2020).

Apart from potential GHG savings, the fuel switch offers further advantages such as:

- Improved local air and noise quality
- Motor longevity of the motor and low maintenance cost
- Vehicles can be used as localised batteries
- Reductions in scope 1 and 2 emissions when powered with renewable energy
- Reduction in emissions from operation – diesel engines take time to warm up, most GSE travel short distances with multiple stops resulting in excessive exhaust gases (AECOM, 2020)

Special attention needs to be given to the fact that recharging intervals have to be compatible with the airport's hours of operation. Moreover, charging times can be limited in terms of overall peak demand and stationary storage devices might be required.

Different types and sizes of eGSEs exist. Examples are taken from the Jungheinrich product range.[20] Further optimisation of energy consumption can be reached when using the very latest, state-of-the-art batteries, currently Li-Ion technology.

The following pictures show tractors with traction of 28 t and 10 t, respectively.

[20] Example of product range and characteristics: https://media-live2.prod.scw.jungheinrichcloud.com/resource/blob/804858/58097ff68d15870dea60a75a51b82797/ezs-brochure-en-gesamtprogramm-schlepper-pdf-data.pdf

Figure 15: Tractors for Airport Use (left: 28t tow tractor EZS7280, right: 10t tow tractor EZS 570 1000)

Source: Jungheinrich

Actual final energy savings from replacing fossil-fuelled equipment with electricity-driven equipment depends on the equipment replaced. Generally, this can be compared with the situation of substituting fossil-fuelled cars with e-cars. Roughly, fuel consumption (diesel) in litres can be multiplied by a factor of ten to arrive at corresponding consumption in kWh. It can be assumed that fuel savings (final energy) achieved are in the range of 30% – 80%. Calculating with the above mentioned 400 kWh/100km for diesel buses and around 100 kWh/100 km for electric buses (NFZ-Messe, 2020), indicates an equivalent net reduction of 75%.

Actual greenhouse gas savings depend on the emission factor of the replaced fuel (for diesel approx. 2.64 kg CO_2/litre) and the source of electricity used. Where electricity from renewable sources is used, greenhouse gas savings can amount to as much as 100%. Where electricity is taken from the grid, energy savings can actually be negative. Figures in absolute terms also depend on the actual service hours/kilometres involved. As an example, the switch from diesel- fuelled tractors to lithium-ion forklifts saves €220 per tractor and year.[21]

[21] Calculation Jungheinrich: information from Jungheinrich Austria, 21.2.2022, comparison of EFG 320 (forklift) and DFG 320, assuming €1.5 per litre diesel and 1,000 operating hours.

Switch to E-GSE at Stuttgart Airport

Stuttgart Airport, a rather small airport handling 36,000 tons of airmail and airfreight per year started switching to electric-driven GSE in 2018. The first zero-emission, battery-operated technology was purchased to handle passenger and baggage movements on the apron. In 2019, the airport followed suit in the cargo sector by replacing diesel-powered cargo tow tractors with emission-free Goldhofer vehicles. Additionally, since 2017, the airport has been using synthetic fuels in special vehicles for fire brigade or winter services, for which no electrical alternatives are available as yet. This combination of fuel switch measures leads to about an 80% reduction in greenhouse gas emissions in handling operations compared to 2009 (Randall, 2019).

Figure 16: Electric GSE at Stuttgart Airport

Source: (Randall, 2019)

Switch to E-Buses at Brussels Airport

Brussels Airport exchanged its bus fleet to thirty e-buses to move passengers between the gate and their plane. The e-buses emit no (local) CO_2 emissions, are almost silent and are expected to save around 600 tonnes of CO_2 annually (20 tonnes of CO_2 per bus). The charging time is about three hours. Buses can travel approx. 150 km fully charged. Daily average distances at the airport are around 12 km. The overall aim at Brussels Airport is to cut CO_2 emissions by 40% by 2030 (as of 2018, they are 7% off their goal) (AECOM, 2020).

4.6.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Table 13: Key Facts of Measure – Electrification of GSE

Key Facts of Measure – Electrification of GSE	
Investment Cost:	Depending on specific measures, standard size e-bus: €550,000 (at airports potentially less) [22] Tractor (traction 28 t): €75,800 (Jungheinrich EZS 7280) Tractor (traction 10 t): €25,400 (Jungheinrich EZS 770-1000)[23]
Energy Savings: (thermal)	Fuel saving (diesel) for one bus: depending on baseline and daily kilometers (12 km, 40 litres/100 km) – 1,752 litres, equivalent to 17,520 kWh
Energy Savings: (electrical)	(Additional electricity consumption for one bus, depending on the specific vehicle): 4,380 kWh
CO_2 mitigation:	Up to 100% of baseline (for above example: 130 t CO_2 for 30 buses)
Benefits:	• Fuel cost savings • Considerable primary energy saving if run on electricity from renewable sources • Energy-efficient motors with lower maintenance and operational costs, more efficient for short distances than diesel fuelled vehicles • Less noise
Disadvantages:	• Recharging strategy needs to consider overall operating hours and peak demand • CO_2 effect strongly depends on electricity generation mix

[22] https://www.heagmobibus.de/de/faq-elektrobusse#6667
[23] Pricing received from Jungheinrich Austria Vertriebsges.m.b.H., 28.1.2022

4.7 Efficient Baggage Handling System

4.7.1 Baseline Situation and Energy Consumption

Electricity consumption at large airports ranges from 100 – 300 GWh annually. In an airport terminal building (ATB), the baggage handling system (BHS) is categorised as a high energy consuming system. After the BHS, conveying equipment is the main consumer of energy (55% to 70%) (Enter, 2018).

Baggage handling systems are mostly conveyor systems with the function to sort and transport luggage to the correct airport destination. Depending on the size of the airport, they can reach a length of several kilometres. Typically, the conveyer tracks are propelled by hundreds of small motors. BHS are responsible for up to 20% of an airport's total electricity consumption (AECOM, 2020). Based on the above figures, this would mean electricity consumption of about 20 –60 GWh per year.

4.7.2 Suggested Measures of Improvement

Various options to increase energy efficiency include more efficient conveyor belts, multi-carrier systems, and lighter baggage trays. Further optimisation is reached via automation and adaptation of the overall control and monitoring systems, including optimisation of operational and idle time. Further developments, which ultimately should completely replace conveyor belts, lead to the use of smart, autonomous vehicles. An example of an autonomous vehicle used for this purpose is given below.

Figure 17: Autonomous Vehicle

Source: (ThorDrive, 2021)

ThorDrive recently demonstrated its driverless technology in airport ground support equipment at Cincinnati/Northern Kentucky International Airport (CVG). The applied technology uses specific LED signalling to show that the tractor is in autonomous operation.

Camera vision is used to detect colours and objects, which are then classified into categories. Light detection and ranging (LiDAR) detect the surrounding environment, using laser light to generate 3D images of the area. The software stack uses these 3D images to properly respond to encountered objects (ThorDrive, 2021).

Smart autonomous vehicles are also in use at Thor Drive Hague Airport in Rotterdam. A trial phase starting in 2018 was successfully completed in 2019 and the vehicles are being further rolled out at the airport. Energy savings are reported to be up to 50% compared with conventional conveyor belt systems (AECOM, 2020).

State-of-the-art conveyer belt systems are in use at the new Midfield Terminal Complex at Abu Dhabi International Airport.[24] The conveyor belt has a length of 25 km and can handle 19,200 bags per hour. As to energy savings, the electricity demand can be reduced from 520 W/m per conveyor to 124 W/m, meaning a reduction of approximately 75% compared to business as usual. Reported investment costs amounted to approximately €10,500/m (AECOM, 2020).

At UK's Stansted Airport, the upgrade of the baggage handling system included both the purchase of more efficient conveyor belts and chutes and the use of 180 automated carts. The system upgrade, which also led to overall automation of the system came at an investment cost of approximately €83 million (Turner, 2021).

4.7.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Energy savings are partly achieved by the use of more efficient components, especially linear synchronous motors rather than standard linear motors. Further savings are achieved using an optimised control system. High-level control systems like SAC (sort allocation computer system) or SCADA (supervisory control and data acquisition) are used in combination with PLC (programmable logic controller) systems.

Figure 18: Luggage Control System

Source: (BEUMER Group, 2022)

[24] According to recent information, the Terminal is still not in operation. (https://simpleflying.com/abu-dhabi-airport-contract-canceled/)

Efficient baggage handling systems lead to energy efficiency improvements, quicker handling of luggage, less engine idling time and the option of including further safety checks and luggage monitoring. Due to the use of modular systems, further adaptations and availability of spare parts become easier. The applied transfer monitor tool allows an overview of delayed incoming luggage requiring quick transfer and thus minimum connection time between flights (BEUMER Group, 2022).

As with all electricity-related measures, the actual greenhouse gas saving effect strongly depends on the electricity source.

Table 14: Key Facts of Measure – Efficient Baggage Handling System

Key Facts of Measure – Efficient Baggage Handling System	
Investment Cost:	€83 million (system upgrade and purchase of 180 automated carts) (Turner, 2021), €10,500/m state-of-the art conveyor belt (AECOM, 2020)
Energy Savings: (thermal)	-
Energy Savings: (electrical)	Approx. 50% compared to BAU system
CO_2 Mitigation:	9000 tCO_2 for a system with 30 GWh of baseline consumption
Benefits:	• Full system optimisation • Increased speed, safety and control over luggage (for system with overall monitoring concept) • Less engine idling time • Cooler operating environment, thus potentially lower air conditioning load
Disadvantages:	• High investment cost • Potential problems during upgrade (systems used in parallel for ongoing operation)

4.8 Central Utility Plant (Cogeneration, Trigeneration)

4.8.1 Baseline Situation and Energy Consumption

Typically, an airport has several boilers to supply different areas with hot water for heating and domestic hot water use. Also, most airports have multiple cooling units that supply cold air to different areas. Due to the size of airports, the energy demand is usually very high and can be in a similar range to the demand of a small town.

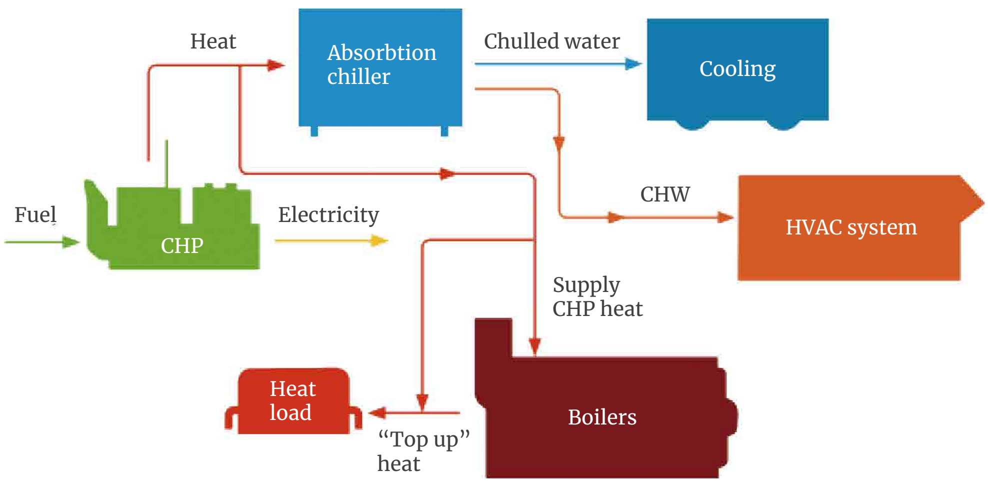
4.8.2 Suggested Measures of Improvement

A central utility plant (CUP) is an integrated alternative to using several decentralised systems. CUPs deliver power, chilled and hot water, and steam to buildings. They are designed to maximise efficiencies from economies of scale, providing large energy and operational cost savings.

The core of a CUP is a cogeneration unit, or a trigeneration unit. A cogeneration unit will use an energy source like natural gas to produce electricity and use the hot air from the turbine to heat water for heat distribution; this process is also known as combined heat and power. A trigeneration unit does the same, but some of the heat is used in adsorption chillers to also supply cold water – it supplies electricity, heating and cooling.

The figure below shows the layout of a CUP that features trigeneration. It consists of a gas turbine, heat recovery for heating and cooling, as well as solar photovoltaics, which can be incorporated into a CUP, if feasible. The heat that leaves the gas turbine is recovered and used to power a steam turbine, chillers and provide heating and cooling for the buildings on site. This is an example of a layout of a CUP that features trigeneration.

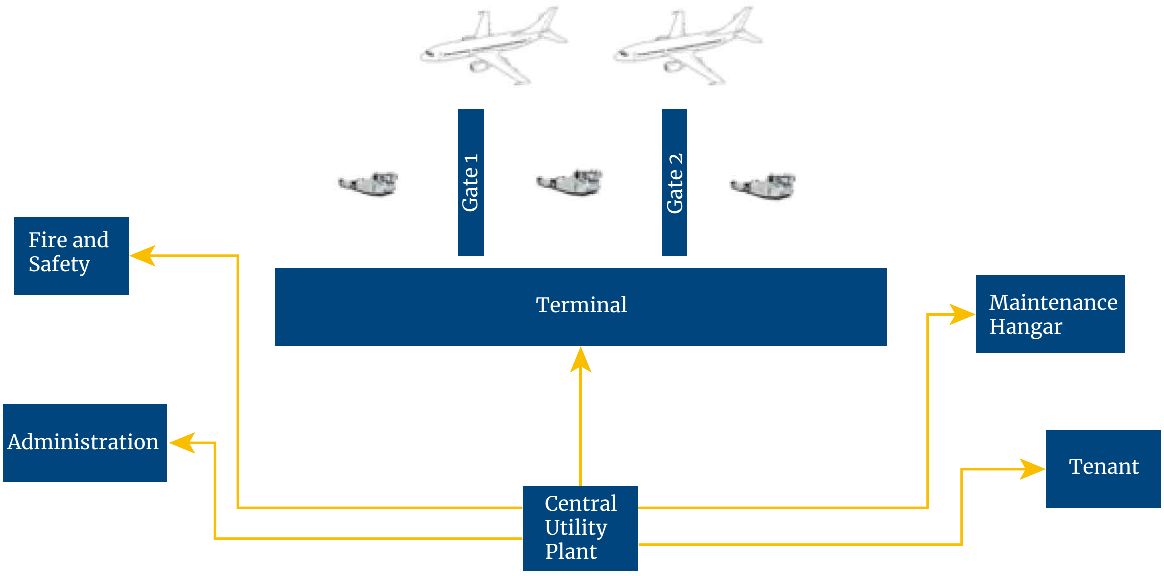
Figure 19: Main Components of a Trigeneration CUP



Source: (GIZ, 2016)

New CUPs can be designed to provide increased resilience to power outages and extreme temperatures associated with climate change. Although cogeneration/trigeneration systems currently on the market are largely based on electricity and natural gas, there are also opportunities for further emission reductions by powering CUPs with renewables and biomass. For large airports, CUPs provide an attractive option to supply energy more efficiently and independently. Typical applications are shown in the chart below.

Figure 20: Energy Transfer using a CUP



Source: (ICAO, 2019)

Los Angeles International Airport (LAX) for instance, began CUP implementation in 2010. "Behind the metal panel and glass façade of the CUP is 20,000 tons of cooling capacity to supply all eight LAX terminals delivered by a plant that includes electric-driven centrifugal chillers, heat recovery boilers, primary and secondary chilled water pumps, cooling towers, and thermal energy storage. An 8.4MW cogeneration plant consists of gas-turbine-driven generators providing electricity and so-called "waste" heat used for heating and to power additional steam-driven chillers." (Arup, n.d.)

Another interesting project is the addition of 4.2 MW of cogeneration at Edmonton Airport in Australia. The total investment cost is about €9.8 million, while the expected annual savings amount to €712,000. The estimated reduction in emissions is between 7,000 and 8,000 tonnes of CO_2-equivalent per year. This retrofit provides a significant reduction of around 20% in emissions, and has a payback horizon of less than 14 years (Atco, 2021).

4.8.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Energy savings when implementing a CUP stem mainly from more efficient energy generation and storage. Cogeneration or trigeneration also ensures maximum efficiency in energy production from natural gas.

Cogeneration or combined heat and power generation is always desirable when both heat and electricity is required. A CUP can be designed specifically to the needs of the airport and thus run at the most efficient load levels. Larger systems typically are more efficient than small ones, thus a CUP will usually be more efficient than a system of decentralised boilers and air conditioning.

Cost and energy savings are strongly dependent on the airport, the energy consumption patterns, the current means of energy production and distribution. A CUP will most likely only be a viable option for an already existing airport, if a new terminal building is being constructed. Retrofitting an airport with a CUP only to replace existing HVAC equipment will not be economically feasible.

Table 15: Key Facts of Measure – CUP

Key Facts of Measure – Central Utility Plant	
Investment Cost:	Heavily dependent on the capacity of the CUP and the method of energy generation.
Energy Savings: (thermal)	-~25% of savings compared to business-as-usual, dependent on size of the airport.
Energy Savings: (thermal and electrical)	~25% of savings compared to business-as-usual, dependent on size of the airport.
CO_2 mitigation:	Up to 100%, depending on the energy source(s) chosen
Benefits:	• Increased resilience against electricity grid failures • Reduced maintenance
Disadvantages:	• High investment cost • Long payback period • Often requires a dedicated CUP building • Specialised maintenance may be required

4.9 Photovoltaic & Storage

4.9.1 Baseline Situation and Energy Consumption

The baseline situation is the respective electricity generation mix currently applied at an airport. The grid emission factor, or the emission factor of the airport's electricity mix, determine potential CO_2 and primary energy savings achievable through renewable energy use. Grid emission factors from various countries can be derived from the IGES database. In the case of China, the respective value amounts to approximately 0.6 t_{CO2}/MWh.

4.9.2 Suggested Measures of Improvement

The switch to less carbon intensive electricity generation can considerably reduce primary energy consumption. Photovoltaic (PV) systems are among the most commonly used renewable energy systems at airports. PV systems have been installed at more than 100 airports worldwide.

Airports are well-suited for PV systems due to the vast horizontal surfaces on which solar panels can be installed – areas which are hardly used for other purposes. These include(terminal) buildings and unused or otherwise unproductive airport property. Some airports have already linked the harnessed solar energy with airport mobility concepts (power to ground vehicles or charging stations for electric cars in parking areas).

Costs for PV systems have decreased considerably in recent years and are already a financially attractive and technically feasible option (ICAO). In many cases, feasibility is often increased through various incentives, although these differ from state to state.

Apart from actual possibilities to connect the plant to the electricity grid, important limiting factors at airports that must be considered in the planning stage involve challenges concerning solar glare and general operational safety implications in terms of specific location and proposed project. Preconditions for permission and acceptance of local stakeholders must be assessed at both national and local level.

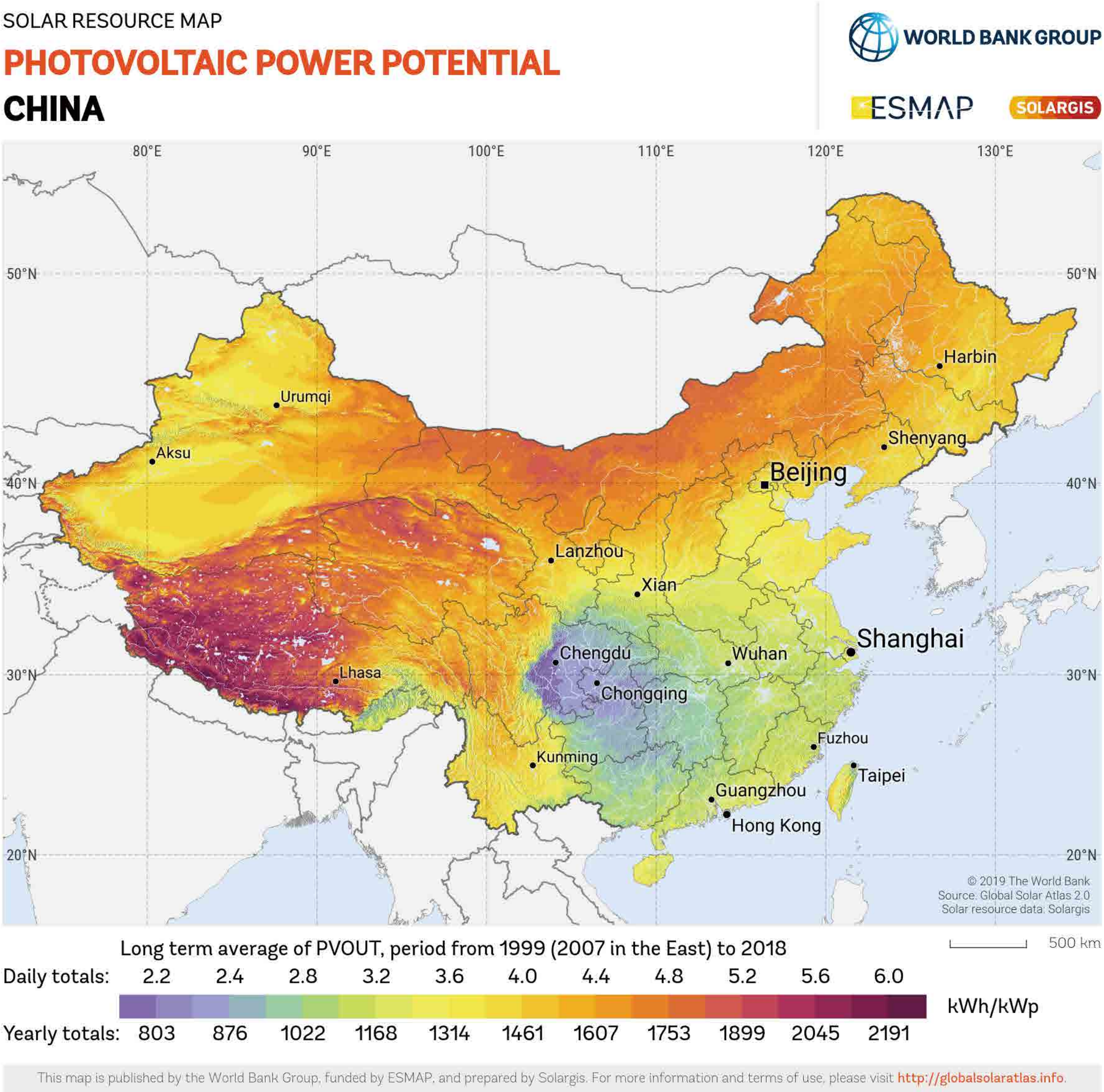
According to ALLPLAN, experience with the following major key facts can serve as initial guidance:

- Installation: roof mounted or ground mounted; typically, East-West mounted with approx. 10° inclination when roof mounted
- Space requirement: approx. 8 m² per kW_{peak} (module alone around 5m², for larger areas 70% – 80% of the area can be used)
- Energy yield: 1,000 – 1,500 kWh/kW_{peak} (depending on location; initial estimates for a given location can be identified via pvgis[25] or using the solar atlas)
- Investment costs: €600/kW – €800/kW_{peak}(might be lower for larger areas)

[25] https://ec.europa.eu/jrc/en/pvgis

In China, the following yields can be expected:

Figure 21: PV Power Potential Chinas, Source: The World Bank



Source: (Global Solar Atlas 2.0, Solar resource data: Solargis 2020[26])

Use of battery systems can help to store excess electricity for times of lower supply and higher demand. Exact dimensioning of both the PV system and battery storage should be performed by expert planners. Planning considerations include: the airport's base load and peak load, plans for airport development/enlargement, the cost of baseline electricity, plans to integrate mobility concepts (e.g., a switch to electric vehicles and fleet) and options to use electricity for heat generation via heat pumps. Solar PV is often a very attractive option when the airport in question requires cooling in summer. In that case, the peak demand for cooling and the peak production of the solar plant also results in optimal use of the plant's potential.

[26] https://solargis.com/maps-and-gis-data/download/china

Case Study – PV at Vienna Airport

Vienna Airport has already installed PV on the roofs of hangars, the cargo centre, the office park, car parks and the old sewage treatment plant. Currently, a ground-mounted PV plant with a capacity of 24 MW_{peak} is being built, which will deliver 30 GWh of electricity per year and cover approx. one third of electricity demand. About 30% of overall electricity consumption will be supplied by photovoltaics (Vienna International Airport, 2021).

Figure 22: Photovoltaics in Vienna

Source: https://noe.orf.at/stories/3125754/

4.9.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

The actual saved energy and GHG emissions depend on the baseline energy supply and the electricity source. Typical sizes of (large) PV plants reach about 20% of baseline electricity consumption. GHG savings can be calculated using the applicable grid emission factor.

Table 16: Key Facts of Measure – Photovoltaic and Storage

Key Facts of Measure – Photovoltaic and Storage	
Investment Cost:	PV: €600 – €800/kW_{peak} Storage: €200 per kWh (storage excl. installation) (ALLPLAN expert estimation)
Energy Savings: (thermal)	-
Energy Savings: (electrical)	Up to 100% (depending on size of the PV plant)
CO_2 Mitigation:	0.7 $kgCO_2$/passenger [27]
Benefits:	PV: • Established technology • Vast potential of shadow-free, otherwise unused spaces at airports • Increasingly financially attractive • Scalability • Options to include mobility and heat concepts Storage: • Reduction of peak electricity consumption • Improves energy supply resilience • Further improvements and financial attractiveness expected
Disadvantages:	• Relatively high upfront costs • Large spatial requirements for storage devices

[27] Assuming 20% electricity generation by PV and 0.6 t CO_2/MWh emission factor)

4.10 Optimisation of Building Envelope Insulation

4.10.1 Baseline Situation and Energy Consumption

Walls, roofs, foundations and floors represent the largest external areas of buildings and are responsible for most heat loss from buildings. Proper insulation reduces heat loss in cold weather, keeps out excess heat in hot weather and helps maintain a comfortable indoor environment. There are many types of insulating material, and certain types are better suited to different applications. A variety of insulation types and additional information relative to their performance and application are shown in Table 17.

Table 17: Characteristics and Applications of Different Insulation Types

Thermal performance level	Highest		High	Moderate	Low	Applications/Comments
Thermal conductivity (W/mk)	0	0.01	0.02	0.03	0.04	0.05
Vacuum insulated panel (VIP)						Research underway in EU and North America to enbed VIPs in EPS or XPS as part of EIFS systems with adhesives to avoid fastener penetrations.High material cost.
Aerogel						For highly constrained space and thermal bridges, such as stud caps. Case studies underway for interior installations with wall board to reduce labour and offer lower systems level cost. High material cost.
Polyurethane boards and spray						Wide applications for value-added performance with space limitations. Roof decking. cathedral roof structures, wall cladding. SIPS, basement, slab edge, and spray foam for cavities also offers air sealing benefits. Higher price premiums with many cost effective applications.
Extruded polystyrene (XPS)						Wide applications for value-added performance with space limitations. Roof decking, wall cladding, SIPS,basement, slab edge, and also offers air sealing benefits. Moderate price premiums with many costeffective applications.
Expanded polystyrene (EPS)						Wall cladding and a dominant choice for EIFS, SIPS, ICFs, and interior applications. Moderate price premiums with many cost effective applications.
Glass fiber						Widely used as cavity insulation alone or with spray foam (flash and batt") to offer more affordable but sealed applications. Used in attics with less space constrained applications.generally lower cost and lower performing applications.
Stone fiber						Used as cavity and in attics with less space constrained applications, generally lower cost and lower performing applications.
Cellulose						Used as cavity and in attics with less space constrained applications, generally lower cost and lower performing applications. New formulations doped with phase change material and passed fire rating tests but has very limited market.
Wood fiber,flax, hemp,cotton,other						Variety of generally lower cost and lower performing insulation applications.

Notes: W/mK= watts per metre kelvin; EIFS = exterior insulation finish systems; SIPs= structural insulated panels; ICFs= insulated concrete forms; PCM- phase change material.

Source: (IEA, 2022)

With rising cost of energy and increasing urgency to limit emission levels, more costly and more efficient insulation is becoming increasingly attractive. It is important to keep in mind that a big part of the cost does not relate to the insulation material itself but to the work involved in insulation. Despite its expense, insulation can be beneficial in the long run as it will make future work unnecessary. All of this shows the need for accurate life-cycle costing (LCC) of insulation for big buildings such as airport terminals. The primary drivers that determine optimal levels of insulation are climate, energy costs, heating system type and efficiency, and the installed insulation costs.

The IEA lists "advanced envelope" as the highest priority for the Chinese building sector, when comparing different energy efficiency measures (IEA, 2022).

4.10.2 Suggested Measures of Improvement

Areas of a building that can be insulated are the walls, the roof, floors and the foundation. The walls and roof of an existing building can be insulated relatively easily, the foundation should remain untouched for obvious reasons.

Exterior wall insulation is common practice in the EU and in most developed countries. Ideally, walls are insulated with a layer of insulation attached to the building's surface before rainscreen cladding is applied. A very common approach on most recent buildings in Europe and on services sub-sector buildings in North America is to add an exterior insulation finishing system (EIFS), also known as an external thermal insulation composite system (ETICS), which embeds insulation under a stucco or cementitious type of finish (IEA, 2022).

Exterior insulation can be applied to existing buildings. It is highly effective, but expensive when retrofitted. It is usually only financially viable when paired with other measures, such as a reduction in space conditioning equipment. When applied to existing buildings, the options are much more limited – usually an exterior insulation finishing system (EIFS) is used. EIFS are usually glued directly to an existing wall, although depending on the material of the wall in question, wall plugs may be required.

Roofs can be separated in two categories; pitched and flat. For airport buildings, usually flat roofs are chosen. Flat roofs exist in two categories, cold roofs and warm roofs. The positioning of the insulation determines the category. Cold roofs position the insulation between the rafters, where as warm roofs have the insulation above the structural deck. Cold roofs are less common now, since more parts of the structure suffer from the thermal effects against which the insulation offers protection.

Insulation can be added to existing roofs, as with walls, LCC (Life-Cycle Costing) will determine the optimal thickness and material. The thickness may be limited due to access doors or the parapet. When retrofitting an existing roof, it is recommended to ensure that air sealing is a high priority as well.

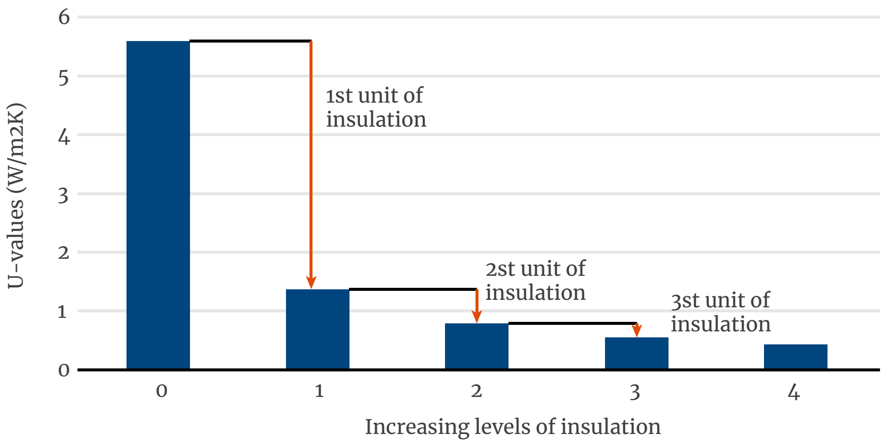
The foundation is usually insulated on the outside, much like walls. Insulation against soil is much more important in colder climates than hot ones, as the soil is usually cool throughout the entire year. Floors above the foundation can be retrofitted with insulation far more easily, and this is a recommended measure in cold climates. Since barriers against water vapour and water are far more important, thermal insulation is often not the best choice here.

It is recommended that efforts be focused on the roof and walls, especially for existing buildings. Roofs and walls offer easier and more effective solutions that can be retrofitted if needed. Both areas require LCC to determine the optimal levels of insulation and, of course, construction standards – such as safety standards – need to be complied with.

4.10.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Insulating any part of a building will provide diminishing returns with increasing levels of insulation. Comparing different levels of insulation shows that doubling the amount does not yield double the savings.

Figure 23: Diminishing Returns of Multiple Insulation Levels



Source: (IEA, 2022)

When constructing a building or when retrofitting an existing building, a fundamental principle is to insulate to the greatest level that is justified, based on life-cycle costs. The marginal cost of installing better insulation is generally low compared to the total cost of installation. If a minimal amount of insulation is installed, it may have an immediate efficiency improvement, but large savings will not be achieved and future retrofits are unlikely to be cost effective. Higher levels of insulation can also be justified during new construction or deep renovation by considering the full-system impacts that allow for downsizing of mechanical equipment in accordance with life-cycle cost assessment (IEA, 2022).

Table 18: Key Facts of Measure – Insulation of Building Envelope

Key Facts of Measure – Insulation of Building Envelope	
Investment Cost:	Highly dependent on the material and thickness of the insulation, as well as the building. Insulation material and thickness can be chosen to fit into an existing budget.
Energy Savings: (thermal)	Depending on current insulation and investment, typically varies between 30% (upgrade of existing insulation) and up to 90% (without previous insulation).
Energy Savings: (electrical)	Depending on current insulation and investment, typically varies between 20% (upgrade of existing insulation) and up to 50% of the required cooling energy (without previous insulation) (Ozel, 2013).
CO_2 mitigation:	Varies; typically, between 15% and 65% CO_2 emissions due to HVAC.
Benefits:	Can increase energy efficiency without any moving parts that can malfunction Can help to achieve a more comfortable climate in the building Well documented and widely accepted technology Parameters can be chosen to fit project optimally
Disadvantages:	If not done properly, small spaces between plates of insulation can draw in humidity, resulting in discolouration and potential damage to the building Requires expert calculations to avoid over and underinvestment

4.11 Savings Achieved with Architectural Design Choices

4.11.1 Baseline Situation and Energy Consumption

Aside from the building envelope, architects can influence a building's energy demand in several other ways. A building's energy transfer via radiation to the surroundings is mostly dictated by its total surface area, the U-Value of the surface and the temperature differential to the surroundings.

The actual layout of the building can help decrease the heating and cooling load, as it defines the total surface area. Aside from the total surface area of a building, windows play a special role, as solar irradiation can partially pass through and heat up the interior. The direction and shading, as well as the size of the windowed area, strongly influence how much energy is needed to maintain a constant temperature.

4.11.2 Suggested Measures of Improvement

Building orientation

Most user guides and manuals on passive solar technologies recommend that buildings should face southwards, although there is a growing consensus that the best option is to orient buildings 20° – 30° to the south to minimize energy usage. "Facing" in this context is the orientation of the largest side of the building. The table below shows the variation in energy savings based on the building's orientation and shape. In the case in question, the orientations were south, east and west, the highest savings were achieved when orientation was southwards.[28]

Another important aspect of orientation is the direction of the glazed surface. Glazed surface, mostly made up of windows, allows sunlight to heat the building in colder months.

Table 19: Comparison of Energy Consumption with Different Building Orientations

	Energy consumption at three orientations (kWh/year)					
	South	%	East	%	West	%
Heating	186	0	231	24	219	18
Cooling	281	0	286	2	369	31
Total	467	0	517	11	588	26
Tmax (℃)	26.4		26.6		27.0	

Source: (Pacheco, Ordónez, & Martínez)

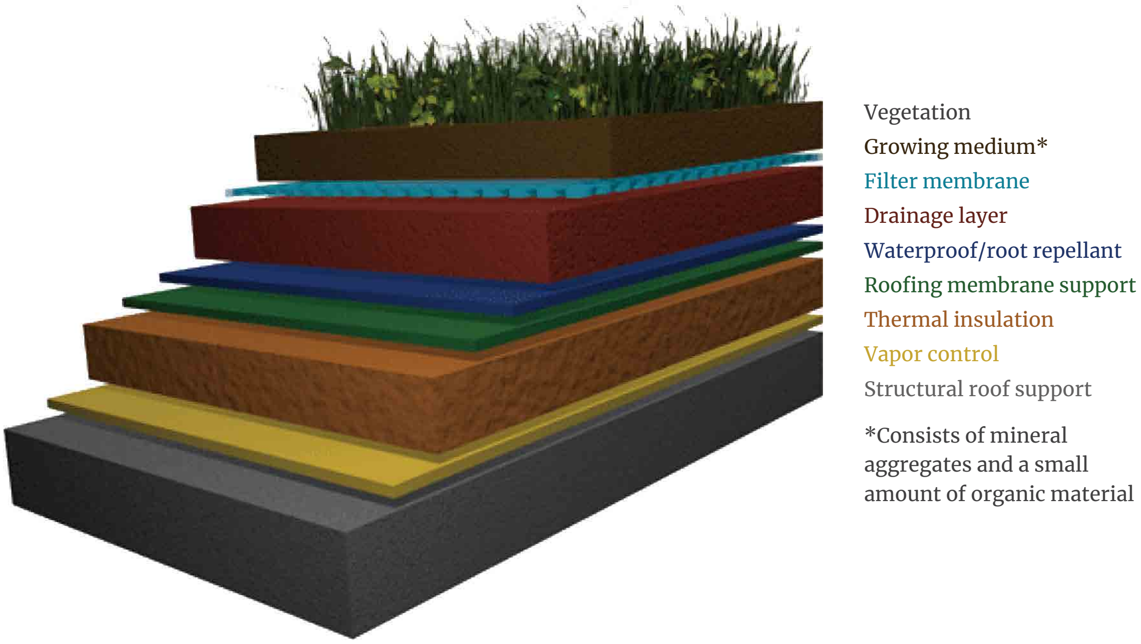
Local geographical conditions also play a role. For example, mountains can heavily influence the amount of direct sunlight at certain times of the day (Pacheco, Ordónez, & Martínez).

[28] The optimum of 20° – 30° facing south has not been calculated here

Green Roof

A ‘green roof,’ i.e. plants on the roof, can substantially lower heat absorption and heat loss, and thereby reduce energy needs. Further, it can reduce storm-water runoff and noise pollution in the area.

Figure 24: General Structure of a Green Roof



Source: (Services, 2022)

Green roofs are categorised into extensive and intensive green roofs. The main difference is the depth of the soil. An extensive roof will have a thin layer of soil and therefore only a very limited number of plants will grow. An intensive green roof has much deeper soil and is suitable for a larger variety of plants. However, an intensive roof requires more expertise to design, has greater weight and higher costs.

Natural lighting

Natural lighting can be employed to substantially reduce the lighting load. Natural lighting, coupled with sensors and smart lighting, can ensure sufficiently lit rooms while reducing the use of electric lighting to times when the available sunlight is not bright enough. Lighting control allows the electric lighting to assist when needed without being fully switched on. This can be done by dimming or by having a set number of LEDs switched on at certain brightness levels. For example, at 500 lux of sunlight irradiation in the morning, only a third of the LEDs might actually be required. Later in the day, those LEDs could turn off, if not needed, and then turn on again to ramp up to 100% of LEDs being switched on at night.

Solar shading

External shading can reduce the cooling load in buildings. Studies have shown that retrofitting external shading can result in savings of between 20% and as much as 35%. The most common retrofit chosen was metal louvers. There are multiple other options, but usually a static external shade is not as efficient overall, as it reduces the heat brought into the building not only in summer, but also in winter. Solar irradiation in the winter reduces the heating load and is therefore desirable (Alhuwayil, Mujeebu, & Algarny, 2018), (Alam & Islam, 2016).

Further measures

Further architectural measures are not addressed in-depth, as their effectiveness is usually lower and most of them cannot be retrofitted. However, during the building planning phase it is highly recommended to look into the following technologies:

- High-performance windows with low thermal transmittance and climate-appropriate solar heat gain coefficient (SHGC)
- Highly reflective surfaces in hot climates, including both white and cool-coloured roofs and walls
- Properly sealed structures to ensure low air infiltration rates with controlled ventilation for fresh air
- Minimisation of thermal bridges (components that easily conduct heat/cold), such as high thermal conductive fasteners and structural members
- Passive solar design that optimises the building's orientation and the placement of windows and shading, and allows for natural ventilation (IEA)

Generally, new buildings should be designed in an energy efficient way with a reduced surface area, if appropriate. Building mass can also be an important factor – it will serve as heat storage and can help stabilise the temperature in a building over short periods of time.

4.11.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

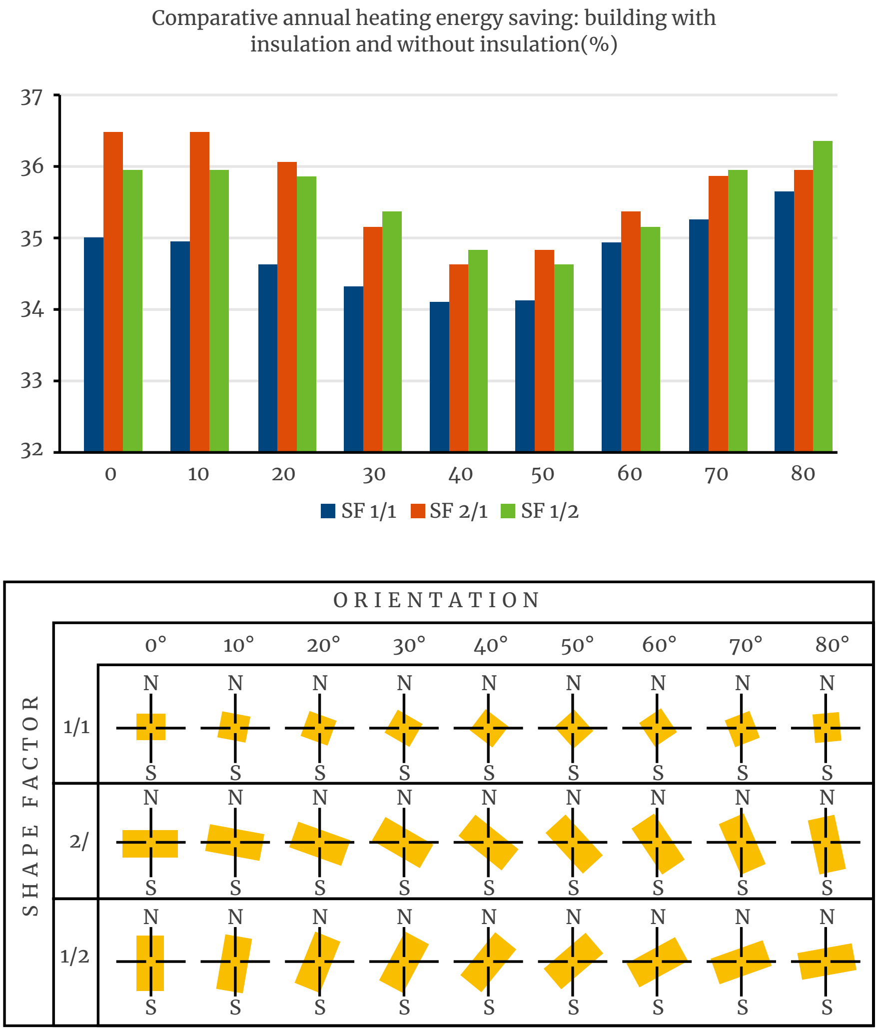
Generally speaking, with the right compactness, orientation and building envelope, energy requirements can be significantly reduced. However, given the potential for cross effects on other areas, case-by-case evaluation is recommended.

Building Orientation

The chart in Figure 25 shows the percentage of heat savings due to solar irradiation in winter on the y axis and the angle of the building on the x axis. Savings also depend on the shape factor (SF).[29] The highest savings for a rectangular building are achieved when the largest glazed wall is orientated south, or south +10°. The highest savings for a square building are achieved when faces south -10°.

[29] SF 1/1, SF 2/1 and SF ½ represent different shape factors, as can be seen in the graphic. SF 1/1 is a square building, SF 2/1 is a rectangular building with the larger wall facing south, SF 1/2 is rectangular building with the larger wall facing east.

Figure 25: Energy Savings in Relation to Insulation, Shape and Orientation



Source: (Pacheco, Ordónez, & Martínez)

The orientation of a building is a major factor that influences the energy efficiency in newly constructed buildings. Figure 25 shows the different energy consumption levels of the same building at different rotation angles. The direction given is the direction of the glazed surface, the side with the most windows. The reason south is the best orientation is that in summer months, the sun will mostly shine on the building from the west and from above, therefore the least-preferable orientation is westwards. During the winter it is quite different – as the sun does not rise as high as in summer, the most sunlight will hit from the south. The savings achieved in this simulation are up to 26% in total energy consumption, of which as much as 31% of the electricity required for cooling could be saved (Pacheco, Ordónez, & Martínez). Assuming average baseline emissions of 4.1 $kgCO_2$ per passenger for HVAC, divided into 1.54 kg/passenger for heating and 2.56 $kgCO_2$/passenger for cooling,[30] the emission reduction amounts to 2.66 $kgCO_2$/passenger.

It is deemed ideal to have a rectangular building orientated south with a variance of no more than 20° and a square building orientated south-west at about 45° to the south. This achieves the ideal balance between the reduction of cooling and heating load.

[30] based on the example of Kansai Airport

Green roofs

Green roofs have the potential to contribute to energy saving and function as an (additional) layer of insulation. Even in warmer climates, energy savings are typically higher in heating than in cooling. For uninsulated, moderately insulated and highly insulated roofs, retrofitting a green roof results in savings ranged from 2% to 44%. Therefore, it is more attractive in economic terms to use green roofs on less insulated roofs.

Retrofitting a roof is usually possible for commercial buildings, as the only restriction is the weight that's added, and whether the construction can bare this load, which is typically about 120 – 150 kg/m². Cost for retrofitting is dependent on several factors, like the type of roof and the plants needed for the climate, but can usually be expected to be between €80/m² and €120/m² (Castleton, Stovin, Beck, & Davison, 2010).

Table 20: Energy Savings with a Green Roof with Varying Types of Insulation

Roof construction	U-Value without green roof (W/m²K)	U-Value with green roof (W/m²K)	Annual energy saving % for heating	Annual energy saving % for heating	Total annual energy saving
Well insulated	0.26-0.4	0.24-0.34	8-9%	0	2%
Moderately insulated	0.74-0.80	0.55-0.59	13%	0-4%	3-7%
Non insulated	7.76-18.18	1.73-1.99	45-46%	22-45%	31-44%

Source: (Castleton, Stovin, Beck, & Davison, 2010))

Natural lighting

Natural lighting has been shown to substantially reduce the electricity required for lighting. The simulation of a cigarette factory in China has shown that electricity required for lighting could be reduced by nearly 50% when installing natural lighting (Zhu, Li, & Li, 2017). Presumably, the reduction would be smaller for an airport that has different operating hours.

Solar shading

Solar shading showed high potential for all major regions, including China, and should be considered a valuable retrofit or installation option, especially in a hot climate. An average of 33% savings in cooling energy with shading was achieved by simulating metal louvers. "After several studies were made metal louvers of 0.5 m were chosen for energy efficiency. Metal louvers are cost effective, available, flexible, durable and environmentally friendly" (El-Darwish & Gomaa, 2017).

Table 21: Key Facts of Measure – Building Orientation

Key Facts of Measure – Building Orientation	
Investment Cost:	Highly dependent on the overall planning
Energy Savings: (thermal)	31% of heating energy
Energy Savings: (electrical)	24% of cooling energy
CO_2 mitigation:	1.2 kg/passenger
Benefits:	• Only planning required, no other resources
Disadvantages:	• Must fit general concept of the airport, extra cost can be generated by longer transportation ways.

Table 22: Key Facts of Measure – Natural Lighting

Key Facts of Measure – Natural Lighting	
Investment Cost:	Case specific
Energy Savings: (thermal)	-
Energy Savings: (electrical)	Up to 50% of the electricity for lighting
CO_2 mitigation:	Up to 1.3 kg/passenger
Benefits:	• Natural light is seen as more pleasant
Disadvantages:	• -

Table 23: Key Facts of Measure – Green Roof

Key Facts of Measure – Green Roof	
Investment Cost:	€80/m² – €120/m² for retrofitting a normal roof to make it a green roof
Energy Savings: (thermal)	8% – 47% dependent on installed insulation
Energy Savings: (electrical)	0% – 45% of electricity for cooling, dependent on installed insulation
CO_2 mitigation:	0.25 kg/passenger if installed on a moderately insulated roof
Benefits:	• Can reduce storm-water run-off, serves as sound insulation
Disadvantages:	• Additional load on roof

Table 24: Key Facts of Measure – Shading

Key Facts of Measure – Shading	
Investment Cost:	€60/m² - €100/m² plus installation
Energy Savings: (thermal)	-
Energy Savings: (electrical)	33% of cooling energy
CO_2 mitigation:	0.84 kg/passenger
Benefits:	• Reduction of UV rays, which can be harmful to some materials • Higher comfort level due to the reduction of heat from direct sunlight
Disadvantages:	• Retrofitting of controlled shading can lead to thermal bridges if done incorrectly

5 Conclusions

Airport buildings are very energy intensive, their total annual energy consumption can reach the levels of small cities, and is hence worth optimizing.

Due to the constantly changing heating and cooling load, one major aspect is proper design and efficient operation of HVAC. In terms of energy sources, the major share of energy consumption is normally attributable to electricity. An airport's energy consumption depends on its size, the surrounding climate condition, the overall comfort level in the airport, the extent of services provided at the airport, the operational hours and passenger numbers. Thus, all comparisons among airports in terms of energy consumption per passenger or per area should be treated with caution.

The most promising energy saving potential is seen in:

- Energy-efficient HVAC
- Architectural improvement
- Energy management and control
- Energy supply efficiency and renewable energy use
- Efficiency of transportation of passengers and baggage

For all measures related to a fuel switch to electricity, we point to the importance of considering the actual source of electricity production and the resulting emission factor. As long as electricity is largely based on fossil fuels, the overall greenhouse effect will be negative. However, with an increasing renewable energy share in the electricity mix, this situation will change in the future. We strongly advocate energy management and control measures (also as a basis for further optimization) as both a short-term and near-term solution. In the longer term, onsite photovoltaic electricity generation should play an important role in the decarbonisation of electricity-based systems, such as HVAC and electric GSE.

Table 25 summarises the main findings of this report.

Table 25: Overview Key Facts

Measures	Key Facts of Measures				
	Investment Cost	Energy Savings (thermal and electricity)	CO_2 Mitigation	Benefits	Disadvantages
Ground Water Cooling	Open loop system €580/KW – €1,000/kW	80% for cooling without reversed heat pump (HP) and open loop system compared to standard chillers; 20% – 30 % with HP and any geothermal loop system	Up to 650 tCO_2/MW cooling capacity	• High electrical savings • Short payback time possible <2.7 years • Low maintenance costs • Scalability and suitable for large cooling loads • Can be used for heating and cooling	• Higher capital costs compared to standard chillers
Adjusting Temperature and Humidity	Approx. €0.2/m² in annual costs (software and manpower)	Up to 20% for heating Up to 20% for cooling	Up to 20% of baseline HVAC related CO_2 emissions	• Pre-defined setpoints easy to implement • Improves thermal comfort and overall efficiency at the same time	• Time consuming data collection and pre-processing for implementing advanced environmental controls
Cold and Heat Storage	Highly depending on the specific situation Pit storage for example €0.4/kWh – €0.6/kWh	Up to 30% for heating Up to 80% for cooling	Up to 2.8 kg per passenger	• High savings in electrical and thermal energy • Pairs well with technologies that produce excess heat (e.g. Solar Thermal, CHP) • Scalability	• Not all technologies can be retrofitted • Depending on the system, especially thermal pits may have considerable heat losses • Not suitable for cold areas
Building Analytics Technology	Annual cost: €1.4/m² (base cost + annual labour cost)	20% (of overall energy consumption)	20%	• Reflecting the energy efficiency of key energy-using systems and equipment • Strengthen the communication and training to raise employees' awareness of energy conservation • Integration with different environmental management system possible (ISO14000, ISO 50001) • Improved occupant comfort	• Limited information on the true costs and potential savings from using varying degrees of analytics • Problems integrating data into the EMIS • Lack of clarity on differences between EMIS products • Lack of existing metering in place

Measures	Key Facts of Measures				
	Investment Cost	Energy Savings (thermal and electricity)	CO_2 Mitigation	Benefits	Disadvantages
Sustainability Rating Systems	Depending on system and size of building, approx. €16,000	Assumption: 10% - 20%	Assumption: 10% – 20%	• Comprehensive analysis of various aspects of energy and resource efficiency • Motivation for improvement for sub-sequent upgrades • Clearly visible ratings	• Effort of implementation
Electrification of GSE	Depending on specific measure: standard E-BU: €550,000; tractor Li-Ion battery (28 t): €75,800 (10t): €25,400	Fuel saving (diesel) for one bus: depending on baseline and daily kilometres (12 km, 4 litres/100km) – 1,752 litres, equivalent to 17,520 kWh; (Additional electricity consumption for one bus, depending on the specific vehicle), i.e., 4,380 kWh	Up to 100% of baseline (for example: 130 t CO_2 for 30 buses)	• Fuel cost savings • Considerable primary energy saving if run by electricity from renewable sources • Energy efficient motors with less maintenance requirement and operation cost, more efficient for short distances than diesel fuelled vehicles • Less noise	• Recharging strategy needs to consider overall operating hours and peak demand • CO_2 effect strongly depends on electricity generation mix
Efficient Baggage Handling System	€83 million (upgrade and 180 automated carts), €10,500/m state-of-the art conveyor belt	Approx. 50% compared to BAU system For baseline consumption 30 GWh this would mean 15 GWh savings	9000 tCO_2 for a system with Baseline Consumption 30 GWh	• Full system optimisation • Increased speed, safety and control over luggage (for system with overall monitoring concept) • Less idling time of motors • Cooler operating environment, thus potentially lower air conditioning load	• High investment cost • Potential problems during upgrade (double systems in parallel for ongoing operation)
Central Utility Plant	Heavily dependent on the capacity of the CUP and the method of energy generation. Cost in the tens of millions of euros is to be expected	25% of savings compared to business-as-usual, dependent on size of the airport	Up to 100%, depending on the energy source(s) chosen. usually ~25% due to energy savings	• Increased resilience against failures of the electrical grid • Reduced maintenance	• High investment cost • Long payback period • Often requires a dedicated CUP building • Specialised maintenance may be required

Measures	Key Facts of Measures				
	Investment Cost	Energy Savings (thermal and electricity)	CO_2 Mitigation	Benefits	Disadvantages
Photovoltaic and Storage	€600-800/kWpeak, €200 per kWh (storage excl. installation)	Up to 100% (depending on size of the PV plant)	0.7 kg CO_2/passenger (assuming 20% of baseline electricity consumption, 20% share, 0.6 t CO_2/MWh emission factor (IGES, China)	PV: • Established technology • Vast potential of shadow-free otherwise unused spaces at airports • Increasingly financially attractive • Scalable to electrical demand and available space • Options to include mobility and heat concepts driven by electricity Storage: • Reduction of peak demand electricity consumption • Improves energy supply resilience • Further improvements and financial attractiveness expected	• Relatively high upfront cost • Large spatial requirements for storage devices
Insulation of Building Envelope	Highly dependent on the material and thickness of the insulation, as well as the building. Insulation material and thickness can be chosen to fit into an existing budget	Thermal 30% (upgrade of existing insulation) –- 90% (without previous insulation) 20% (upgrade of existing insulation) – 50% of the cooling load (without previous insulation)	15% – 65% of HVAC related CO_2 emissions	• Can increase energy efficiency without any moving parts that can malfunction • Can help to achieve a more comfortable climate in the building • Well documented and widely accepted technology • Parameters can be chosen to fit project optimally	• If not done properly, small spaces between plates of insulation can draw in humidity resulting in discolouration and potential harm to the building • Requires expert calculations as to not over- or underinvest
Building Orientation	Dependent on the overall planning	31% of heating 24% of cooling	1.2 kg/passenger	• Does not require material	• Must fit general concept of the airport, extra cost can be generated by longer transportation ways.
Natural Lighting	Case specific	Up to 50% of the electricity for lighting	Up to 1.3 kg/passenger	• Natural light is seen as more pleasant	• Regular maintenance can be required

Measures	Key Facts of Measures				
	Investment Cost	Energy Savings (thermal and electricity)	CO_2 Mitigation	Benefits	Disadvantages
Green Roof	€80/m² - €120/m²	8% – 47% thermal energy dependent on installed insulation 0% – 45% of electricity for cooling, dependent on installed insulation	0.25 kg/passenger if installed on moderately insulated roof	• Can reduce storm-water run-off, serves as sound insulation	• Additional load on roof
Shading	€60/m² - €100/m² plus installation	33% of electricity for cooling	0.84 kg/passenger	• Reduction of UV rays, which can be harmful to some materials • Higher comfort level due to the reduction of heat from direct sunlight	• Retrofitting of controlled shading can lead to thermal bridges if done incorrectly

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