Developing an Airport Energy System Optimisation Framework

The Example of Amsterdam Schiphol

Master Thesis

Aerospace Engineering - Control & Operations

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Christoph Pabsch

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by

Christoph Pabsch

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Student number:	5064015	
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Thesis committee:	Ir. P.C. Roling,	TU Delft, supervisor
	Dr. A. Bombelli,	TU Delft
	Dr. J. Sun,	TU Delft
	Dr. A.C. Braz,	EPFL, supervisor

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Christoph Pabsch
Sion, February 2025

Contents

List of Abbreviations

APU	Auxiliary Power Unit
EU	European Union
HFSP	Hybrid Fuzzy-Stochastic Programming
HOMER	Hybrid Optimisation Model for Electric Renewable
HVAC	Heating, Ventilation and Air-Conditioning
IPESE	Industrial Process and Energy Systems Engineering group at EPFL
KPI	Key Performance Indicators
LP	Linear Programming
MCDM	Multiple Criteria Decision Making
MILP	Mixed Integer Linear Programming
PEM	Polymer Electrolyte Membranes
PSO	Particle Swarm Optimisation
PV	Photovoltaic Cells
REMM	Rational Exergy Management Model
SAF	Sustainable Aviation Fuel
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysers
SQP	Sequence Quadratic Programming

Introduction

Airports are key mobility hubs in the current century. They connect humanity across different continents and allow fast transport of passengers and goods. Airports are thus enabling aviation and have a significant impact on the economic development of their surrounding region [1]. Nevertheless, airports also have negative impacts, both on their neighbouring environment and on the climate. They create noise and environmental pollution [2] and are a significant energy consumer. Reducing their energy consumption could thus have an important local and global effect towards a more emission-free world.

The Industrial Process and Energy Systems Engineering (IPESE) group at EPFL, where this thesis has been conducted, has substantial expertise in the domain of energy system engineering, the integration of renewables and the design of complex energy systems. Research domains of this group include the topics of process integration, process design, urban systems and energy planning [3]. Several tools were developed by the group for modelling and optimising energy systems. One of them is OSMOSE, a tool for designing and analysing integrated energy systems, which has been used for the optimisations performed in this study.

In the thesis, an energy system optimisation framework is developed, allowing the analysis and comparison of various technology configurations for different airports. The demand is estimated using a simple model applicable to any airport. It is developed based on data obtained from contacts at KLM and Amsterdam Schiphol Airport. Next, a superstructure of energy technologies is built up, which includes models defined based on literature as well as (adapted) models from the IPESE group. Together, the energy demand model and the energy system optimisation framework in OSMOSE allow to answer the research question of this thesis, which is defined as follows:

> *„To what extent could European airports, such as Schiphol airport, benefit from the concept of renewable energy hubs in reducing their sustainability impact and increasing their energy supply self-sufficiency while fulfilling the varying energy demand profile from airport operations and infrastructure?“*

This thesis report is split into two separate parts. Part I includes the scientific article, which contains the research performed during the thesis, including the methodology and results for estimating the energy demand and optimising the energy system. In Part II, the literature review is presented, the research gap is identified and a research plan is developed.

I

Scientific Paper

Developing an Airport Energy System Optimisation Framework: The Example of Amsterdam Schiphol

Christoph Pabsch[1,2]

Supervisors: Ana Catarina Gouveia Braz[2], Paul Roling[1]

Abstract

Airports play a significant role in economic development while presenting considerable energy consumption with demands from various stakeholders. Their important environmental impact can be reduced through an optimised energy system design. In this study, a systematic framework for the generation and comparison of airport energy systems is developed. Mixed integer linear programming and multi-objective optimization are employed to generate different system configurations, which are then compared using multi-criteria analysis. The airport energy demands are estimated based on a simple model for the building and the airfield handling area, using a limited set of parameters available for any airport. First results for Amsterdam Schiphol and five other European hub airports indicate that fully renewable energy systems can be competitive, especially when integrating battery storage for daily energy management. Self-sufficiencies of around 80% can be economically viable, relying on energy systems employing photovoltaic cells, a CO_2 network, batteries and grid electricity.

Nomenclature

Abbreviations

AEC	Alkaline electrolyser
BAT	Battery
BOI	Boiler
CC	Combined cycle
CHI	Chiller
CO2N	CO_2 network
DHW	Domestic hot water
EDDM	Munich airport
EHAM	Amsterdam Schiphol airport
ENGM	Oslo-Gardermoen airport
FT	Fischer-Tropsch
GSE	Ground support equipment
GWP	Global warming potential
H_2S	Hydrogen storage system
HP	Heat pump
HVAC	Heating, ventilation and air conditioning
Inv	Investment cost
LEMD	Madrid-Barajas airport
LIRF	Rome-Fiumicino airport
LSZH	Zurich airport
Op	Operating cost
PEM	Proton-exchange membrane
PV	Photovoltaic cell
SOEC	Solid oxide electrolyser
SOFC	Solid oxide fuel cell

Latin Symbols

A	surface area	m^2
$ACPH$	air changes per hour	-
C	cost	€
C_p	specific heat capacity	kJ/kg/K
COP	coefficient of performance	-
d	distance	m
D	Frequency of occurrence	-
DA	people degree of activity	-
$\dot{e}$	electricity load	kW
E	electricity	kW
E_{sp}	specific electricity demand	Wh/m^3
En	energy	kW
es	energy stored	kWh
Ex	exergy	kW
f	unit sizing factor	-
F	fixed unit size	-
G	global warming potential	tCO_2eq
GI	global incident radiation	W/m^2
$\dot{h}$	natural gas load	kW
H	height	m
hc	heat exchanged heat cascade	kW
ir	interest rate	-
I	irradiance	W/m^2
k	factor	-
l	layer	-

[1]Department of Control & Operations, Faculty of Aerospace Engineering, TU Delft
[2]Industrial Process and Energy Systems Engineering, EPFL

lt	lifetime	y
LF	load factor	-
MET	standard metabolic heat human	W
n	number	-
P	power	kW
$\dot{q}$	heat load	kW
RES	renewable electricity share	-
rs	resource stream	kg/h
SS	self-sufficiency	-
t	time	s
T	temperature	°C
U	thermal transmittance	$W/m^2/K$
v	velocity	km/h
$\dot{V}$	volume flow	m^3/h
y	binary variable unit installation	-
YC	yearly annualised costs	€/y
YG	yearly greenhouse gas pot.	tCO_2eq/y

Greek Symbols

α	weight objective function	-
ϵ	fraction/share	-
η	efficiency	-
ξ	recovery rate	-
ρ	density	kg/m^3
ϕ	solar transmission factor	-
Φ	heat input power	W/m^2
Ψ	fresh air ratio	-

Subscripts

b	building
c	consumption
cell	cell
ch	charging
cw	cold water before heating
cond	condenser
d	daily
dhw	domestic hot water
dr	driving
ea	electric appliances
el	electrical/electricity
en	energy
evap	evaporator
ex	exergy
ext	exterior
f	flight
fa	fresh air
g	gains (solar and interior)
gen	generator efficiency
h	hourly
hc	heat cascade
hw	hot water after heating
II	second law
in	going in
int	interior
irr	solar irradiation
level	level of energy storage
max	maximum
med	median
min	minimum
out	going out
p	period
pax	passenger
pr	process
r	rated
rad	radiation
real	real
s	stream
STC	standard test condition
sw	swept
t	time instance
th	theoretical
T	Temperature
u	unit
ut	utility
v	vehicle
vs	ventilation system
wa	building wall
wi	building window
wt	wind turbine
y	yearly

Superscripts

+	imported
-	exported
cap	capital
dem	demand
el	electricity
fuel	fuel
gr	grid
inv	investment
GSE	ground support equipment
loc	local
min	minimum
ng	natural gas
nr	non-renewable
op	operating
ren	renewable
wt	wind turbine
PV	photovoltaic

Sets

$\boldsymbol{U}$	set of units
$\boldsymbol{L}$	set of layers
$\boldsymbol{P}$	set of periods (typical days)
$\boldsymbol{T}$	set of time instances
$\boldsymbol{S}$	set of streams

1 Introduction

Airports have a significant importance for economical development of their surrounding region due to their function of moving cargo and people [1]. Overall, there are more than 2000 airports in Europe [2], moving 2.3 billion passengers [3]. On the other hand, airports also have an important environmental impact, which is not only coming from the aircraft emissions but also from other sources such as ground support equipment, heating and cooling of the airport or construction work for renewing its infrastructure [4]. In fact, Amsterdam Schiphol emitted more than $75,000\mathrm{tCO_2eq}$ in 2023 [5], being equivalent to the emissions per passenger for 160,000 flights from Amsterdam to New York [6].

The airport's energy system is the main contributor to the airport's emissions. Amsterdam Schiphol consumed over 254GWh of energy in 2023 [5]. This is equivalent to the electricity consumption of nearly 100,000 households per year [7] and thus twice the household electricity consumption of a small city like Delft [8], [9]. Data from 20 European airports allows to make an estimate of an average energy demand of 6.3kWh passenger [5], [10]–[32], which would lead together with the yearly total number of 2.3 billion passengers in 2023 [3] to an energy consumption of 14.5TWh for all European airports together in one year, which is equivalent to the annual electricity production of smaller European countries like Croatia [33].

In consequence, there is a huge potential to reduce energy consumption and CO_2 emissions of airports by a smart design of integrated airport energy systems, both through a good choice of energy technologies as well as by reusing waste or excess energy. Creating a universally applicable optimisation model for designing energy systems, which can be used in different environmental characteristics, could thus help in creating a baseline for developing and renewing energy systems of airports.

The goal of this research is to develop an energy system model to analyse to what extent European airports, such as Amsterdam Schiphol, could benefit from the concept of renewable energy hubs in reducing their sustainability impact and increasing their energy supply self-sufficiency while fulfilling the varying demands from airport operations and infrastructure. A renewable energy hub connects different energy storage and conversion technologies to optimise their performance and maximise renewable energy use [34].

The energy demand is estimated from airport operational, structural and weather data, which can be gathered for any European airport, and includes the building as well as the airfield handling demand. Hourly profiles are obtained, which are clustered in typical days as input for the energy system optimisation. An extensive superstructure is constructed, including various technologies for heating, cooling, local electricity production and storage as well as the possible production of synthetic fuels. The energy system is optimised and the energy demand is balanced using the OSMOSE tool for designing integrated energy systems [35]. Possible configurations are analysed using a set of key performance indicators including costs, global warming potential (GWP), exergy efficiency, self-sufficiency and renewable electricity share.

A simple but robust model for estimating the energy demand and designing the energy system has been successfully developed and has been applied to the case of Amsterdam Schiphol and five other European hub airports. First results indicate an energy system consisting of a combination of photovoltaic cells (PV), electricity from the grid, a battery, a CO_2 network and a combined cycle from natural gas to be most robust. A fully renewable energy system is achievable at only slightly higher costs. The introduction of energy storage technologies is beneficial, especially when not using natural gas. Batteries for daily energy storage appear to be the most beneficial energy storage option. A fully self-sufficient airport is possible at high investment costs, whereas self-sufficiencies of 80% are observed to be economically viable.

This paper will start with a description of relevant literature in section 2. Next, the methodology, both for estimating the energy demand and designing the energy system, is described in section 3. The case studies employed in this research are depicted in section 4. Results are presented and analysed in section 5, before section 6 concludes this research with overall conclusions and recommendation for future work.

2 Related Work

Airports are complex systems, having a diverse set of stakeholders, energy demands and limitations to take into account. A description of the environment in section 2.1 is followed by a summary of relevant research in the fields of airport energy demand estimation and system optimisation in section 2.2 and section 2.3 respectively. To conclude, section 2.4 identifies the research gaps addressed by this study.

2.1 Airport Environment and Energy Demand

Aviation, being a main driver of globalisation, relies on globally present airport infrastructures, with large economic centres often also being close to large airports [36]. They thus have a key role in the current transportation system. The largest airports move more than 100 million passengers per year [37].

Many different stakeholders are involved in an airport, including the passengers, the air carriers, the airport authority and service providers as well as local organisations, communities and governments [38]. Their interests are diverse, ranging from efficient and smooth airport operation, minimal costs, growing passengers numbers and maximum revenue up to a minimised impact on the environment and local communities.

The airport itself can be divided in two main parts: the landside area consisting of for example passenger terminal buildings, freight terminals and parking lots as well as the airside area consisting of the terminal airspace, taxiways, runways, etc. [39].

Due to their size, airports have a high energy consumption, with Amsterdam Schiphol having an energy consumption of $254 GWh$ for moving 61.9 million passengers in 2023 [5]. The yearly energy consumption for 20 European airports can be seen in Figure 1. While in general the demands increase with the number of passengers, significant variations can be observed due to different airport layouts, energy systems and measurement methods. Looking at the energy usages for six airports where data is available [12]–[14], [16], [17], [21], it can be observed that direct electricity demand is the most important with 57% of the overall demand on average, followed by heating with 31%, cooling with 12% and fuel with 12 %. The most important energy resources are observed to be electricity from the grid, natural gas and diesel [10], [11], [15], [18], [23], [24].

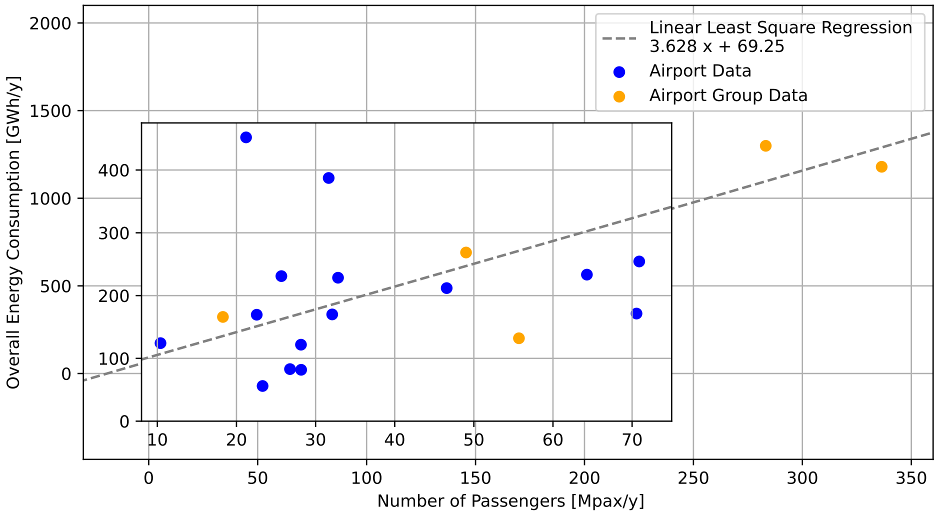


Figure 1: Overview of energy demands per number of passengers of a selection of 15 individual European airports and five European airport groups [5], [10]–[32]

Reducing an airport's energy demand is of crucial importance for reducing its environmental impact. Possible pathways would be for example optimised operation [40] or the introduction of new technologies such as renewable electricity sources, energy-efficient technologies or electric vehicles [41].

2.2 Energy Demand Estimation

The energy demand of the airport can be divided in the airside and landside parts of the airport. Ortega Alba [42] further subdivided the areas and the main facilities, being for example lighting, heating, ventilation, etc. and defined hourly up to seasonal demand profiles, finding that the time of day and the season determine most the energy demand. Lin, Liu, Zhang, et al. [43] observed that the highest energy demands occur in climate zones with hot summers and/or cold winters. The energy consumption in a freezing environment can be two to four times higher than in mild environments [44]. Furthermore, the terminal surface area and the flow of passengers have an important influence on the buildings' energy demand [43], as well as the spatio-temporal distribution of the passengers in the building [45].

An optimal energy system that is based on different types of requirements and resources can be computed after having detailed information and estimation on the energy demand, in terms of the type of demand (electricity, thermal, fuel), the location of the demand and the variation over the year, as is also done in the approach of Rubeis, Nardi, Paoletti, et al. [46]. Studies on modern terminal buildings, such as the one performed by Xianliang, Jingchao, Zhiwen, et al. [47], suggested that the systems related to heating, cooling and ventilation are the largest energy consumers and the ones with the most significant distribution over space and time. Moreover, Yildiz, Yilmaz, and Celik [48] suggested changing the set-point temperature for heating and cooling and renewing those technologies as some of the main strategies for reducing energy demand and emissions. However, substantial reductions in emissions can also be achieved by optimising other systems in the building environment, such as the baggage handling system, as is studied by Lodewijks, Cao, Zhao, et al. [49].

As regards the vehicles around an airport, it can be seen that the majority operates on the airside area with activities related to aircraft loading, towing, take-off preparation or others, as is described by Liu, Li, Liu, et al. [50]. Vehicle energy demand is found to be dependent on the flight schedule especially for the airside vehicles related to aircraft handling [50]. The demand of airside ground support equipment can be decreased through more efficient operation. Sigler, Wang, Liu, et al. [51] for example optimised routes and schedules of shuttles at the airport to decrease the energy consumption of the airport. Moreover, Zoutendijk and Mitici [52] are optimising the schedules of aircraft towing vehicles at limited energy supply to study the effect of an increased electricity demand of the airport due to the introduction of electric towing vehicles. Indeed, many airports are working towards fully emission-free ground handling, such as Amsterdam Schiphol, where the ambition is to achieve emission-free ground operations by the year 2030 and where, in 2023, 30 new electric ground power units are introduced in order to reach this goal [53].

Finally, future energy demands of green aviation can be considered when estimating the energy demand of airports. Radhakrishnan [54] studied the effect of additional electricity demand due to electric aviation at Stavanger airport, which might double the current energy demand within the next 20 years, and found that it is difficult to transform the airport into a positive energy district only by the introduction of renewable power generation from PV at the airport.

2.3 Energy System Optimisation

In parallel to energy demand estimation, energy system optimisation can be done either for the terminal buildings, the airport operations or a combination of both. Most studies focus on the terminal building energy system. For optimisation, linear programming is mostly used, allowing to find a solution from an objective function and set of constraints, both being linear functions of the decision variables [55]. Mixed-integer linear programming furthermore allows to determine an optimal solution from both integer and non-integer variables. Sequence quadratic programming [56], particle swarm optimisation [57], hybrid fuzzy-stochastic programming [58] and multiple criteria decision making [59] are observed to be alternative options. Moreover, specific tools for the optimisation of energy systems exist and are used, such as the Hybrid Optimisation Model for Electric Renewables developed by the National Renewable Energy Laboratory in the United States [60] or the modular open-source OSeMOSYS framework employed by Prussi, Laveneziana, Misul, et al. [61].

Multiple studies investigated energy system optimisation of airport buildings. Most of them looked into a combination of heating, cooling and power supply [58], [62]–[64], while some of them only considered individual demands such as only power supply [59], [60], only power and cooling supply [56] or only thermal demands [65]. Some of the studies consider in addition to the building energy demands the vehicle demands at the airport [61] or additional demands due to electric aircraft, as was done by Tian, Zhang, and Balta-Ozkan [57], who optimised the full energy system including buildings and mobility demand.

Different conclusions are observed for the building energy system. Jin and Li [58] identified that the optimal share of grid electricity significantly depended on the grid electricity price. Similarly, Zhang, Si, Feng, et al. [56] described how it can be beneficial to use different cooling technologies during night and day based on the natural gas and electricity prices. Renewable energy generation at the airport can reduce the dependence of the grid. In fact, local renewable electricity production technologies often have lower levelised costs than grid electricity, as was found for PV energy by Thiem, Danov, Metzger, et al. [62]. However, for PV it is important to consider the limitations due to glare effects on the pilots at the airport. Next to PV, wind energy can be considered as an alternative local resource for emission-free airports [64]. Rubeis, Nardi, Paoletti, et al. [46] propose the combination of solar and wind power with energy storage technologies for load management and specifically suggest to replicate this approach to other European airports. Natural gas generators could be a non-renewable alternative for levelling electricity supply [57]. For heating and cooling, combined technologies of heating, cooling and/or power are observed to show a high potential [58], [62], [66].

From the different studies, it is observed that through new integrated building cooling, heating and power systems, the costs of the energy system can be decreased or even profitable energy systems might be obtained [56], [62], [63]. However, Zhang, Si, Feng, et al. [56] also noted that the most cost-effective solutions are not necessarily equivalent to the most energy-efficient solution [56], indicating a trade-off to be made between different parameters. In general, these results must be analysed with caution, as the simulations have limitations, due, for example, to the assumptions made, which might lead to good but not necessarily globally optimal results, as is mentioned by Baek, Kim, and Chang [60].

For the ground support equipment, Kirca, McGordon, and Dinh [67] investigate how emissions could be reduced through electrified ground support equipment as well as optimized charging schedules and battery pack sizes. For the future, it is suggested to look into adding vehicle-to-grid operations. Another option for ensuring electricity supply for the ground support equipment is the introduction of hydrogen. Including a hydrogen storage system would allow to power for example the aircraft auxiliary power unit and to increase the overall energy system efficiency, as was seen by Xiang, Cai, Liu, et al. [68]. Furthermore, in combination with PV energy, hydrogen allows to compensate for insufficient availabilities of grid electricity [69].

2.4 Research Gap

Multiple studies already examined the energy demand of airports and introduced methods for optimising their energy systems. However, most of these studies only focused on the demand estimation or the energy system optimisation, while for the latter, most studies did not optimise the full energy system but focused on one part, being for example the heating and cooling system, the buildings or the ground support equipment charging. Furthermore, most of the studies focused on one airport. The research gap identified for this study lied thus in an all-encompassing approach for estimating the airports' energy demand as well as constructing the airports' energy system, by using an approach globally applicable to any airport location with a limited set of pre-defined airport parameters. The model shall allow to analyse the performance of a variety of energy technologies, including possible production methods of sustainable aviation fuels, which has not been explored in the studies discussed.

3 Methodology

The methodology for this thesis comprises both the energy demand estimation as well as the construction of the energy system for the airport. Thus, in this section, first the methods for estimating the energy demand and for obtaining and clustering the optimisation input data are explained in section 3.1 and section 3.2 respectively. Subsequently, section 3.3 describes in detail the energy system superstructure constructed for this study. Finally, section 3.4, section 3.5 and section 3.6 explain the employed optimisation framework, the possible objective functions and the chosen key performance indicators.

3.1 Energy Demand Estimation

The energy demand of an airport consists of several components. Figure 2 shows an example of the yearly energy consumption distribution of Amsterdam Schiphol [70]. It can be observed that the main consumers of energy are the airport terminals and piers. Other significant consumers are buildings such as hotels around the airport, hangars and warehouses, charging and shore power, parking and aircraft handling. The other consumers show only a minor share of 2% or less. This study is limited to the energy consumption at the airport related to passenger and flight handling and thus to the terminal and pier buildings and aircraft handling using ground support equipment (GSE), making up 61% of the total energy consumption at Amsterdam Schiphol airport. The methods for estimating those demands are outlined in the following subsections.

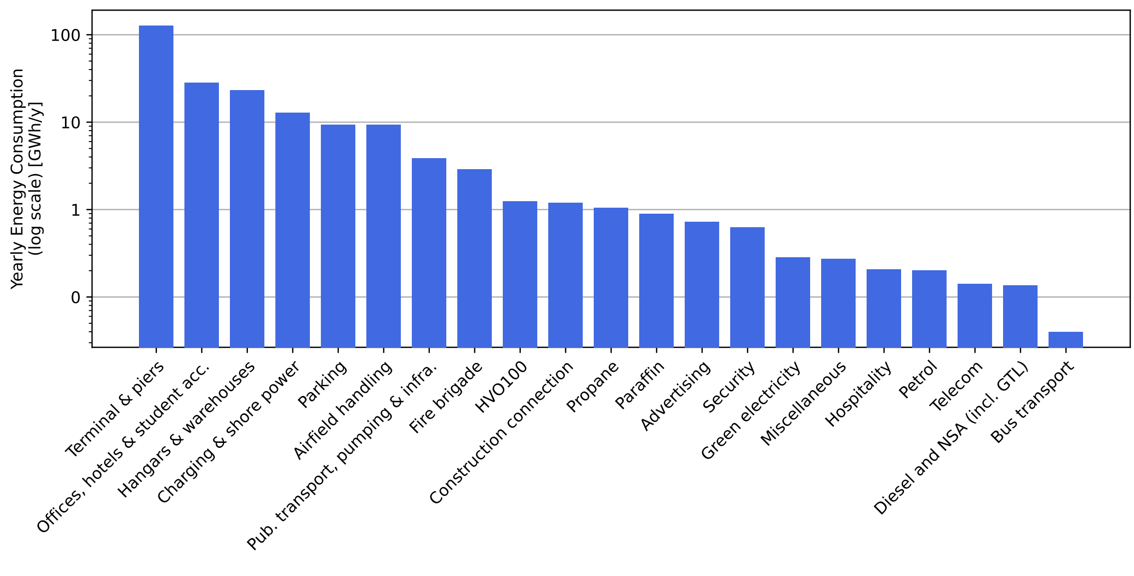


Figure 2: Total Energy Consumption Distribution of Amsterdam Schiphol Airport in 2023 (corrected for primary energy factor in numbers provided) [70]

3.1.1 Terminal and Pier Buildings

The main energy consumption contributors considered are the terminal and pier buildings. An example of the energy consumption distribution of these buildings is shown in Figure 3 [71]. Overall, it can be estimated that 19% of the energy demand is related to air handling, 9% to cooling, 27% to heating, 2% to domestic hot water, and 43% to other electricity consumers, such as lighting or baggage handling. Three types of energy demands will be defined in this study: heating consisting of building heating and domestic hot water, cooling, and electricity consisting of ventilation and other electricity appliances.

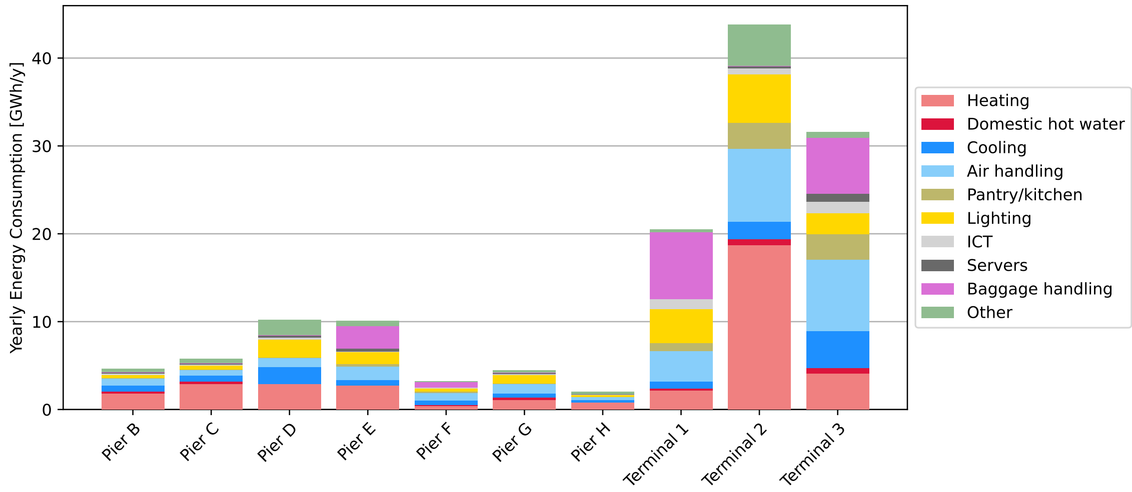


Figure 3: Energy Consumption Distribution Terminals and Piers at Amsterdam Schiphol Airport in 2023 (Note: Terminal 2 also provides climate heating and cooling for Terminal 1, Plaza and Skyport) [71]

Heating and Cooling

In order to estimate the building heating and cooling energy demand, different heat exchanges of the building with its environment as well as its interior are considered. An overview of this is shown in Figure 4. As can be seen, the heat losses from the ventilation system and through the building walls as well as the heat gains from solar irradiance on the building walls and windows, from electric appliances and people in the building are considered to determine the overall heating or cooling demand required to ensure an interior temperature of $T_{int} = 22°\text{C}$, the typical value to which public buildings are heated [72].

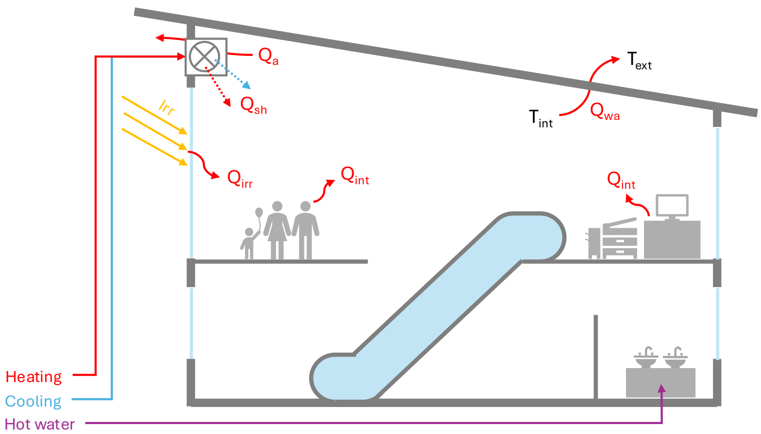


Figure 4: Illustration of the heat exchanges considered for estimating the building heating, cooling and DHW energy demands

$$\dot{q}_{sh} = \dot{q}_g - \dot{q}_{wa} - \dot{q}_{fa} \tag{1}$$

The different contributions seen in the illustration are also reflected in Equation 1, which determines the overall hourly space heating demand $\dot{q}_{sh}$ from the interior and solar gains $\dot{q}_g$, the heat lost through the walls $\dot{q}_{wa}$ and the heat lost through fresh air entering the building $\dot{q}_{fa}$. If $\dot{q}_{sh}$ is negative, no heating but cooling is required to ensure the set-point interior temperature. The model for obtaining the heat and cooling demands is based on a similar building envelope model for residential buildings [34].

$$\dot{q}_g = \dot{q}_{int} + \dot{q}_{irr} = (A_b \cdot \Phi_{ea} + n_{pax} \cdot DA \cdot MET) + A_{wi} \cdot \phi_{wi} \cdot I \tag{2}$$

As shown in Equation 2, the heat gain of the building $\dot{q}_g$ is obtained from two different contributions: the interior gains $\dot{q}_{int}$ and the solar irradiance gains $\dot{q}_{irr}$. The interior gains are on the one hand gains from power appliances, which are calculated from the surface area of the building A_b as well as an estimate of $\Phi_{ea} = 3\text{W/m}^2$ [72] for the heat input power of appliances in similar large-surface areas such as shopping malls or restaurants. On the other hand, there are gains from the building occupiers. They are estimated from the hourly number of passengers in the building n_{pax}, an estimate of $DA = 1.2$ [72] for the degree of activity for people in similar buildings such as shopping malls and a value for the standard metabolic heat (MET) for a human body of $MET = 104\text{W}$ [73].

As a second contribution, building heat gains are occurring due to solar irradiance on the windows, $\dot{q}_{irr}$. They are computed from a window solar transmission factor $\phi_{wi} = 0.65$ [72], an estimate that 80% of the wall area of the buildings is composed of windows, and the wall area A_{wa}. The wall area is obtained from an estimate for the building height of $11m$, based on data, and the building contour length obtained from [74].

$$\dot{q}_{wa} = U_b \cdot (A_b + A_{wa}) \cdot (T_{int} - T_{ext}) \tag{3}$$

Next, the heat lost because of heat exchange through the building walls, $\dot{q}_{wa}$, is determined using Equation 3. This estimate is based on the thermal transmittance of the building envelope, U_b, the surface area of the building, the wall area A_{wa} as well as the interior set-point temperature and the external temperature, T_{ext}. For the thermal transmittance, a value of $U_{b_{roof}} = 0.8\text{W/m}^2/\text{K}$ is used for the building roof and of $U_{b_{wall}} = 1.36\text{W/m}^2/\text{K}$ for the wall area (being composed of 80% windows with $U_{b_{window}} = 1.5\text{W/m}^2/\text{K}$ and 20% opaque surfaces with $U_{b_{opaque}} = 0.8\text{W/m}^2/\text{K}$) [72].

$$\dot{q}_a = ACPH \cdot \Psi_{out} \cdot (1 - \xi_{vs}) \cdot \rho_{air} \cdot C_{p_{air}} \cdot (T_{int} - T_{ext}) \tag{4}$$

Finally, the heat lost due to the fresh air entering with the ventilation system, $\dot{q}_a$, is estimated using Equation 4. The volume flow of fresh air entering the building is calculated by multiplying the required air changes per hour ($ACPH$) of the ventilation system with $\Psi_{out} = 1/3$ of the air going through the ventilation system being replaced with outdoor air, an estimate based on similar ratios of health care public buildings [75]. Furthermore, it is assumed that $\xi_{vs} = 0.73$ [72] of the heat from the replaced air is recovered to the new air entering the building, thus reducing the heating demand. Next to that, an air density of $\rho_{air} = 1.225\text{kg/m}^3$ and a specific heat capacity at constant pressure of $C_{p_{air}} = 1.006\text{kJ/kg/K}$ are used for the exchanged air [76].

Domestic Hot Water

The heating demand of domestic hot water is estimated as follows.

$$\dot{q}_{dhw} = \rho_{dhw} \cdot C_{p_{dhw}} \cdot \dot{V}_{dhw} \cdot (T_{hw} - T_{cw}) \tag{5}$$

As can be seen in Equation 5, the heating demand $\dot{q}_{dhw}$ for domestic hot water is estimated from the required hourly volume of hot water $\dot{V}_{dhw}$, the temperature of the water before being heated up of $T_{cw} = 12.5°\text{C}$ [77] as well as the target temperature of the water after heating and before delivery of $T_{hw} = 60.0°\text{C}$ [78]. Furthermore, a density of water of $\rho_{dhw} = 1{,}000\text{kg/m}^3$ and a specific heat capacity at constant pressure of $C_{p_{dhw}} = 4.186\text{kJ/kg/K}$ are employed [79].

$$\dot{V}_{dhw} = n_{pax} \cdot V_{dhw_{pax}} \tag{6}$$

The hourly volume flow of domestic hot water $\dot{V}_{dhw}$ is computed using Equation 6 from the number of passengers as well as an estimate $V_{dhw_{pax}}$ for the required volume of domestic hot water per passenger. For the latter, a combination of the standard demand of domestic hot water per person in a restaurant (15l/d/pers) and in a shopping mall (1.5l/d/pers) is used [72]. As it can be assumed that 50% of all passengers eat in a restaurant at the airport [80], 100% of the value for a shopping mall and 50% of the value for the restaurant are summed up, leading to a domestic hot water demand per person of 9l/d/pers.

Ventilation

To complete the heating, ventilation and cooling system, the electricity demand for the ventilation system is estimated.

$$\dot{e}_{vs} = \dot{V}_{vs} \cdot E_{sp_{vs}} = (ACPH \cdot A_b \cdot \overline{H}_{b_{int}}) \cdot E_{sp_{vs}} \tag{7}$$

The electricity demand of the ventilation system $\dot{e}_{vs}$ is calculated using Equation 7 from the required overall volume flow of the ventilation system $\dot{V}_{vs}$ and an expected average consumption of new ventilation systems of $E_{sp_{vs}} = 0.28\text{Wh/m}^3$ [81]. The overall volume flow is determined from the building surface area, an estimate of the average inner height of the buildings of $\overline{H}_{b_{int}} = 8.8\text{m}$, being equal to 80% of the estimate for the overall building height, and the required $ACPH$. For the latter, a value of 6 is used, the same as the standard for shopping malls (6), slightly higher than the standard for public waiting rooms (4) and slightly lower than for restaurants (8-12) [82], of which the airport can be estimated to be a combination of.

Electricity

The electricity demand of the remaining energy consumers in the terminal and pier buildings is estimated based on the data of Amsterdam Schiphol airport shown in Figure 3 [71]. Different parameters are used in order to quantify the electricity demand and to determine its profile for the different consumers.

Table 1: Parameters defining the electricity demand of an airport

	Sizing parameters	**Profile determining parameters**
Baggage handling/process	Passenger capacity, surface area	Number of flights
ICT	Passenger capacity	Number of flights
Lighting	Surface area	Constant, daylight hours
Pantry/kitchen	Passenger capacity, surface area	Number of flights
Servers MER+SER	Passenger capacity	Constant
Other	Surface area	Constant

In Table 1, an overview of the different parameters for the different consumers is given. The sizing parameters for the electricity consumption are the yearly passenger capacity of the airport, the surface area or an equally weighted combination of these two. A normalized yearly electricity consumption is subsequently determined, in order to determine the electricity demand for any airport based on these two parameters.

In order to obtain an hourly profile of electricity demand, different parameters as shown in Table 1 are again used. These are either the number of flights, the daylight hours or none of the two, depending on which parameter is assumed to be most relevant. The normalized profile of these parameters is then multiplied with the yearly electricity consumption of every consumer to get a yearly profile.

3.1.2 Ground Support Equipment (GSE)

The second energy consumption contributor considered in this study is the GSE on the airport. For this, the energy demand is estimated based on data obtained from KLM for their GSE employed at Amsterdam Schiphol airport. The data obtained includes all equipment trips in the airport required to serve the KLM and SkyTeam member flights [83]. The daily sums of these trips for the different types of vehicles considered are shown in Figure 5.

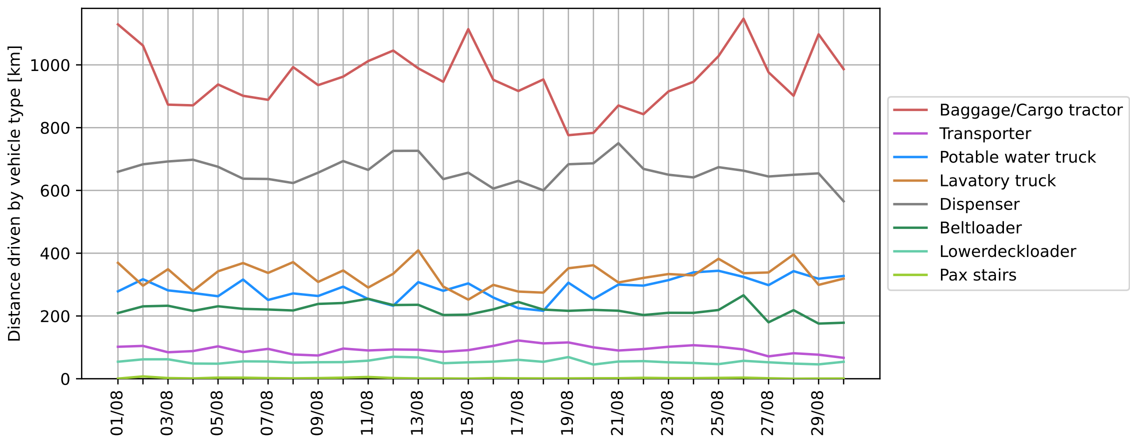


Figure 5: Distances driven by GSE of KLM at Amsterdam Schiphol airport in August 2024 (computed from KLM GSE trip data [83])

In order to obtain the energy demand for the GSE, the average energy demand of GSE per flight is computed. Using the flight profile for a full year, the daily charging demand can then be determined.

$$d_{f_d}^{GSE_v} = \frac{\sum_{i=1}^{tr_d} d_i^{GSE_v}}{N_{f_d}} \tag{8}$$

First, the distance driven by each GSE vehicle type v per flight f on each day d $d_{f_d}^{GSE_v}$ in the period for which the data was obtained can be calculated using Equation 8. This is done by summing the distances $d_i^{GSE_v}$ of every individual GSE trip i on the respective day and dividing them by the number of flights N_{f_d} on that day. Only the flights of KLM and other SkyTeam member airlines are considered, as the GSE for which the data is available only operated these airlines.

$$\overline{d}_f^{GSE_v} = \frac{\sum_{d=1}^{n_d} d_{f_d}^{GSE_v}}{n_d} \tag{9}$$

Next, the average GSE distance per flight $\overline{d}_f^{GSE_v}$ for every GSE type is calculated using Equation 9 by determining the average distance of all days for which data was obtained.

$$\overline{E}_{c_f}^{GSE_v} = P_r^{GSE_v} \cdot \frac{LF^{GSE_v}}{\eta^{GSE_v}} \cdot t_{dr_f}^{GSE_v} \,, \qquad where\ t_{dr_f}^{GSE_v} = \frac{\overline{d}_f^{GSE_v}}{v_{med}^{GSE_v}} \tag{10}$$

Subsequently, the energy consumption for every GSE type per flight $\overline{E}_{c_f}^{GSE_v}$ can be determined using Equation 10. For this, the rated power $P_r^{GSE_v}$, the load factor LF^{GSE_v} and the efficiency η^{GSE_v} for each vehicle type is needed together with the time $t_{dr_f}^{GSE_v}$ the type of GSE is driving. The latter can be obtained using the average GSE distance per flight and an estimate $v_{med}^{GSE_v}$ for the median velocity.

Data for the GSE rated power has been drawn from a GSE manufacturer [84]. For most vehicles, the average rated power from the vehicle portfolio has been determined. For the dispenser and lower deck loader, no data is available and thus the average of all GSE has been used. The load factor has been determined using the average load factor for all activities per vehicle category, which is $LF = 4$ for vehicles of type B and C [67]. Finally, for the efficiency a value of $\eta = 0.75$ is assumed for electric GSE [85].

Table 2: Vehicle category [67] and rated power of GSE for which data is available [84]

Vehicle type	Vehicle category	Rated power [kW]
Baggage / Cargo tractor	B	49.5
Beltloader	C	49.8
Dispenser	B	76.4 (GSE average estimate)
Lavatory truck	B	108.4
Lower deck loader	C	76.4 (GSE average estimate)
Transporter	B	49.5
Potable water truck	B	108.4
Passenger stairs	C	92.9

$$\overline{E}_{c_d}^{GSE} = \sum_{f=1}^{n_{f_d}} \sum_{v=1}^{GSE} \overline{E}_{c_f}^{GSE_v} \tag{11}$$

In order to obtain the average energy consumption $\overline{E}_{c_d}^{GSE}$ per day for all GSE, the average estimated consumptions of all GSE types for all flights on a day can be summed as shown in Equation 11, with n_f being the number of flights on that day. An extra 40% of energy consumption is added for missing types of vehicles such as the aircraft tractors, which is estimated based on the overall aircraft handling energy consumption at Amsterdam Schiphol airport [70]. Accuracy of the model can be improved in the future by using complete data including all types of GSE vehicles instead of an estimate for the missing vehicles' energy consumption.

$$\dot{e}_{ch_t}^{GSE} = \frac{\overline{E}_{c_d}^{GSE}}{t_{ch_d}} \tag{12}$$

Finally, the required electricity for charging needs to be determined. As the GSE need to operate during the whole day, it is assumed that they are only charging during nighttime from 00:00 to 05:00. In consequence, as can be seen in Equation 12, the electricity $\dot{E}_{ch_t}^{GSE}$ required for charging in each of these five hours can be determined by dividing the average energy consumption per day by the possible charging duration per day t_{ch_d} of five hours.

3.2 Input Data Used for Optimisation

To compute the energy demand, different input data are required, as for example weather or flight data. Furthermore, prices for resources are required for later optimising the energy system. It is decided to optimise the energy system for hourly intervals, for all 8,760 hours of the year. Thus, hourly input data for the airport and weather characteristics is required and obtained as described in section 3.2.1. Next, this hourly data is clustered in typical days as described in section 3.2.2, in order to reduce the complexity of the optimisation problem.

3.2.1 Airport, Weather and Resource Cost Profiles

The energy system optimization is performed for an hourly profile. This entails that, for the data varying over the year, an hourly profile is required. This will be the case for performance data of the airport including the number of flights and passengers, for weather data including the position of the sun, as well as for resource prices data.

For the airport performance data, the hourly number of flights can be obtained from the OpenSky API [86]. Using the time instances of all departures and arrivals at the airport in 2023, the number of flight movements (including both departures and arrivals) can be computed for every hour of the year.

It is more difficult to compute the hourly number of passengers at an airport. Most of the airports only publicly provide the monthly passenger statistics, such as Amsterdam Schiphol airport [87]. In consequence, the hourly number of passengers has to be estimated from the hourly number of flights and the monthly passenger profile. The method used is shown in Figure 6. First, for every month the scaling factor between the total number of passengers and flights is computed. Subsequently, average scaling factors in between all months are computed and linearly connected to obtain the variation of the scaling factor at every hour in the month. Finally, in order to obtain the correct overall number of passengers for every month, a parabolic function is added to the scaling factor, adjusting the number of passengers to the monthly passenger profile in an iterative procedure.

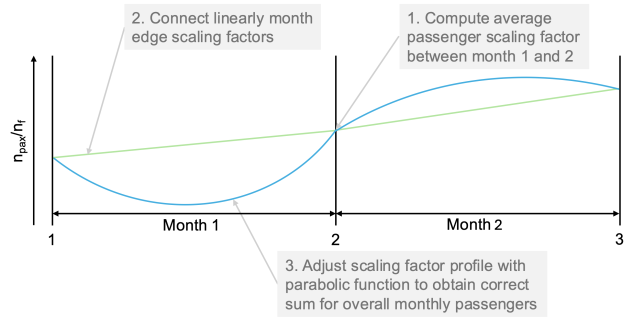


Figure 6: Method for obtaining hourly passenger profile from hourly flight profile and monthly passenger profile

Hourly profiles for the weather data can be obtained from Open-Meteo [88]. The historical API database includes an extensive set of weather data for any location on the Earth, including the solar radiation, the wind speed at different heights, the ambient temperature as well as the daylight duration as required for this thesis. Next to that, the SolTrack Python package [89] can be used to obtain the precise solar position at any location and time in the year, to determine the exact potential of PV power.

For the electricity prices, the Energy-Charts API [90] can be employed. This API database allows to obtain the historical hourly variation of the electricity prices on the different European electricity spot markets. Furthermore, it also allows to obtain the share of renewable electricity at every hour in the year for the different spot markets. Together with the yearly electricity emissions in every country [91], this also allows to obtain the hourly CO_2 emissions of the electricity from the grid, as can be seen in Equation 13.

$$\left(\frac{G_{el}}{E_{el}}\right)_h = \frac{G_{el_y}}{E^{nr}_{el_y}} \cdot \epsilon^{nr}_{el_h} \tag{13}$$

Where G_{el_y} are the overall CO_2 emissions in a year, $E_{nr_{el_y}}$ is the yearly amount of non-renewable electricity and $\epsilon^{nr}_{el_h}$ is the share of non-renewable electricity in that hour.

3.2.2 Clustering Input Data in Typical Days

Optimising the energy system for the hourly profiles obtained for the entire year would lead to high model complexity with in total 8,760 data points. In consequence, it is important to reduce the data size [34] to less data points, which can for example be done by clustering the data in typical days. Using this method, every day in the year is assigned a typical day. The few typical days chosen to represent all days of the year are characteristic days of the year, for example in terms of their weather, and allow to give an approximate image of the entire year, by reducing the size of the problem to less repeating data points. For the final model results, such as the yearly operating costs, the results obtained for the distinct typical days are multiplied by the number of occurrence of every typical day in the full year.

Different methods exist for clustering all days of the year into typical days. From the most common aggregation methods, the k-medoids method, which is minimising the sum of the deviations of all clusters, displays overall the best performance [92]. The code used for clustering has been adapted from the code employed in the REHO energy optimisation framework [93].

For clustering, a number of 12 typical days are chosen. Two extreme hours are added, which complement the data by unrepresented hours with extreme values such as for example solar radiation. The typical days have been clustered based on three weather parameters: solar radiation, wind speed and ambient temperature. Next to those, the electricity price is defining the results and is variable over the year. However, it is assumed that it is dependent on the wind speed and solar radiation and thus its variation is already partly represented by including those two variables.

Having chosen the typical days using clustering methods, the remaining hourly data, both for the demand as well as for other relevant parameters such as the electricity price or grid electricity emissions, is added to the weather data for the typical days. It is used from the same days as the 12 days chosen using the typical day clustering, which is possible as all of the data used is from 2023. This clustered data is the input data used for the optimisation problem, for which energy system structures are computed.

3.3 Energy System Superstructure

The energy system superstructure, as shown in Figure 7, is implemented in order to serve the energy demands from section 3.1 for the typical days determined in section 3.2.2 constructed with the hourly data profiles from section 3.2.1. Next to the pre-defined demands, it consists of the resources and technologies, which will be described in the following subsections. An overview of the costs and impacts defined for all technologies described in this subsection can be found in section 3.3.6.

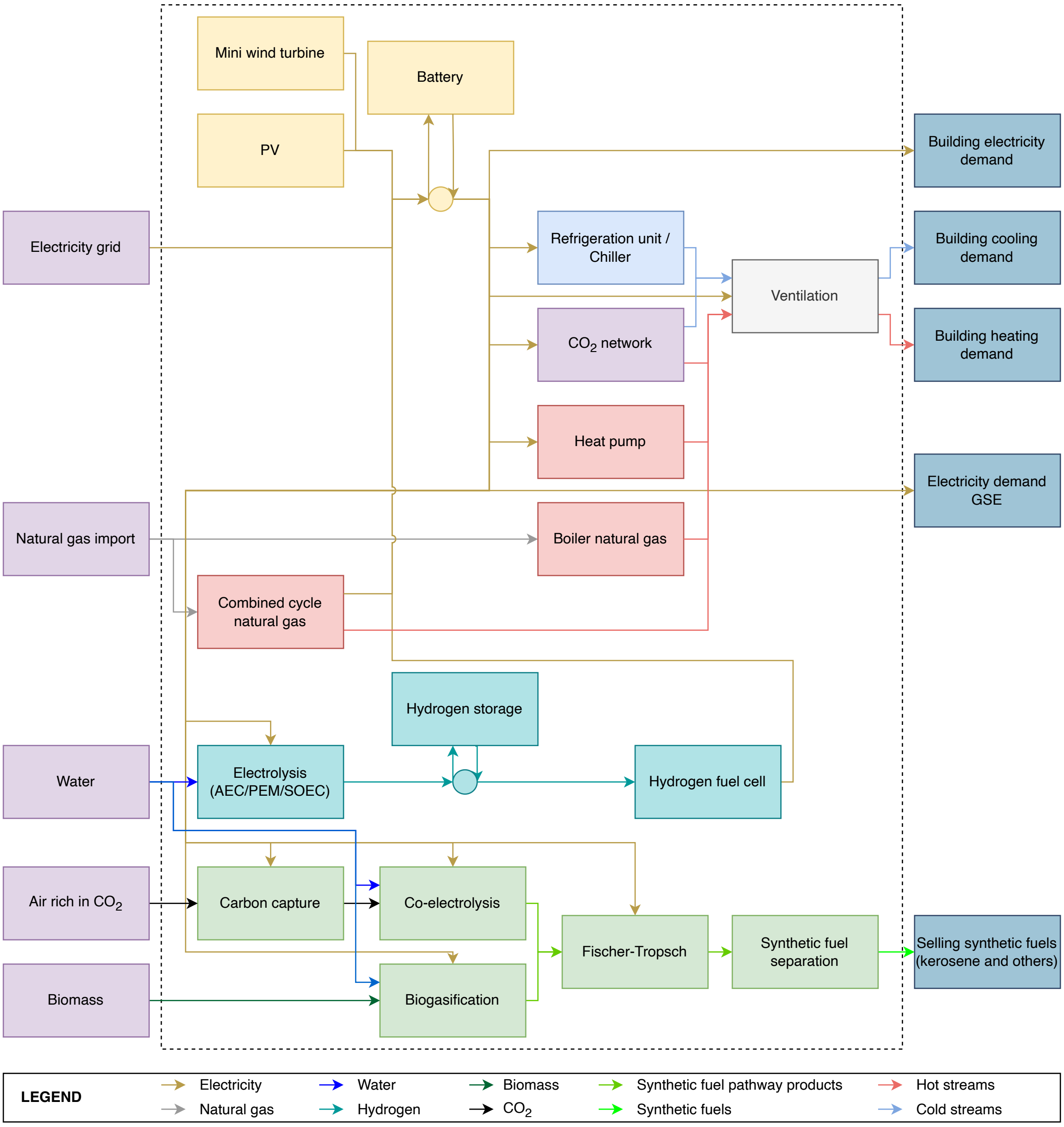


Figure 7: Overall superstructure of the energy technologies implemented with simplified resource flows

3.3.1 Resources

Different resources can be imported to the energy system. First of all, the grid electricity is included in the superstructure with variable prices and variables CO_2 emissions, which are computed as described in section 3.2.1 from Energy-Charts data [90].

The second main resource is natural gas. For its price, the average value of the Dutch TTF Natural Gas price for 2023 of 41.28€/MWh [94] is employed for the full year and no hourly profile is applied. The reason for this is that the natural gas price is not related to varying weather such as the electricity price but depends also on geopolitical factors such as the Russian war against Ukraine [95], which are difficult to predict.

Water, mainly required for the production of hydrogen and synthetic fuels, is for this study assumed to be available at a zero price. It is considered that it could be harvested from the rain on the large airport (buildings) surface or could be obtained from treated wastewater. Additional water would however require the water price of the grid.

The air rich in CO_2 is assumed to be available at zero price from close-by industry. For the case of Amsterdam, it could come from steel industry, which is for example present in Ijmuiden [96]. Also other emission-intensive industries close to the airport would be possible sources of CO_2 being used for co-electrolysis and synthetic fuel production.

Finally, the availability and the cost of biomass are determined based on a tool for biomass chains in the different European countries [97]. The biomass is however not available at a constant price, but different types of biomass are available at different costs, ranging in the Netherlands for 2020 from approximately 1,200kt available at a cost of slightly less than 5€/t up to more than 3,600kt of biomass available when paying costs up to 120€/t. As not a single value can be deduced from the biomass cost profile, varying values will be looked at when analysing the production of synthetic fuels.

3.3.2 Electricity Generation and Storage Technologies

In this subsection, the working principle of the technologies used for local electricity generation and storage is explained. PV and mini wind turbines are technologies implemented for the production of renewable electricity at the airport. It must be added that also the combined cycle can locally produce electricity, which is described later. Furthermore, batteries are installed for storing electricity. Next to that, a model for a hydrogen storage system with electrolysers and fuel cells is included in the superstructure, being described separately.

PV

Local generation of electricity can be performed through solar cells placed on the airport area. Even when limited in locations for placement due to glare and radio effects, there are still sufficient locations on the areas around the airport where the installation of PV is possible [98]. For the PV, a model taking into account the solar irradiation and the position of the sun is used, which calculates the energy produced $\dot{e}_t^{PV}$ based on the following Equation 14 [99].

$$\dot{e}_t^{PV} = \eta_{el}^{PV} \cdot k_{gen}^{PV} \cdot k_{rad,t}^{PV} \cdot \left[1 - k_T^{PV} \cdot \left(T_{cell,t}^{PV} - T_{STC}\right)\right] \cdot GI_t \cdot A^{PV} \ , \qquad \textit{where } t = \textit{time in the year} \tag{14}$$

where $\eta_{el}^{PV} = 0.178$ [99] is the electrical efficiency of the PV module, $k_{gen}^{PV} = 0.95$ [99] is the efficiency factor of the generator electrical conversion, $k_{rad,t}^{PV}$ is a factor taking into account the radiation intensity based on the incident of solar radiation, $k_T^{PV} = 0.004/\mathrm{K}$ [99] is the temperature reduction factor, $T_{cell,t}^{PV}$ and $T_{STC} = 25°\mathrm{C}$ [99] are the actual and standard test condition cell temperature, GI_t is the global incident radiation on the surface of the PV and A^{PV} is the area of the PV.

The costs of the PV are determined based on an estimate of the current cost for commercial high area PV installation [100].

Mini Wind Turbines

The second local production method for electricity are mini wind turbines. They are small wind turbines suitable to the airport environment, which imposes strict physical and electromagnetic or radio easements on their placement [101] not allowing the installation of conventional large wind turbines close to the runways. The energy produced from such small scale wind turbines $\dot{E}_p^{wt}$ is computed from Equation 15 [102].

$$\dot{e}_t^{wt} = \frac{1}{2} \cdot A_{sw} \cdot \rho_{air} \cdot \eta^{wt} \cdot {v_t}^3 \ , \qquad \textit{where } t = \textit{time in the year} \tag{15}$$

An efficiency of $\eta_{wt} = 0.2$ is assumed for the wind turbines for an estimated average wind speed of $\overline{v_t} = 4\mathrm{m/s}$ [102]. The swept area A_{sw} is calculated for an average rotor radius of 9.8m for horizontal axis mini wind turbines, which is used for assuming the cost for each installed wind turbine [103].

Battery

A battery model is implemented in the superstructure as a method for short-term, especially daily, electricity storage. Nickel-Cobalt-Aluminium Lithium-ion batteries are chosen as a technology due to their relatively low current installation cost. They are observed to have a round trip efficiency of 95% and a daily self-discharge rate of 0.2% [104].

3.3.3 Heating and Cooling

Different technologies are implemented for heating and cooling of the airport terminal buildings. These include conventional heating technologies running on natural gas, such as boilers of combined cycles, heat pumps and chillers for electricity-based heating and cooling as well as a CO_2 network as a combined heating and cooling solution. The working principle of the models of all these technologies is described in this subsection.

Boiler Natural Gas

The natural gas boiler is implemented as a simple model [105] for a centralised boiler with a thermal efficiency of 95%. It has a minor consumption of 0.02kW of electricity for every 1kW of useful heat output. As investment costs, costs for similar boilers used in district heating systems are assumed due to the significant scale of the airport's surface area [100]. Due to the scope-1 CO_2eq emissions from burning the natural gas, an impact value is assigned to the boiler [106].

Combined Cycle Natural Gas

As an alternative to the natural gas boiler, a combined cycle is introduced in the superstructure both generating heat and electricity from burning natural gas. The implemented technology model has a thermal efficiency of 40% and an electrical efficiency of 49% [105]. For the costs, investment costs values for conventional combined cycle gas turbines are used [100]. Again, scope-1 CO_2eq emissions have to be added to the technology model by assigning an impact value [106].

Heat Pump

For the heat pump, a simple model is implemented taking heat from water available in rivers, lakes or the sea. The model is based on the calculation of the coefficient of performance COP_{real} displayed in Equation 16 [65].

$$COP_{real} = \eta_{II} \cdot COP_{th} = \eta_{II} \cdot \frac{T_{cond} + 273.15}{T_{cond} - T_{evap} + \Delta T_{evap}^{min}} \tag{16}$$

For the assumed supply temperature which is equal to the exit temperature at the condenser $T_{cond} = 60°\text{C}$, a second law efficiency of $\eta_{II} = 0.423$ can be assumed [34]. A minimum temperature difference of $\Delta T_{evap}^{min} = 2°\text{C}$ can be used at the evaporator [65]. The heat source outlet temperature being the temperature at the exit of the evaporator $T_{evap} = 1°\text{C} - 2°\text{C}$ minus the subtracted superheating temperature difference [65] is inspired from similar values for rivers, lakes and seawater [107].

The investment cost is estimated based on the costs for similar types of heat pumps and their maximal electric power [108].

Chiller

The chiller has a model very similar to the heat pump, as it basically is a heat pump running in reverse mode, releasing the heat to the environment. Hence, Equation 16 [65] still applies for calculating the coefficient of performance COP_{real} of the chiller. Still using the same condenser exit temperature of $T_{cond} = 60°\text{C}$, but now with a minimum temperature difference of $T_{cond}^{min} = 1.5°\text{C}$ at the condenser [65], a second law efficiency of $\eta_{II} = 0.436$ can be applied [34]. Next to that, a minimum temperature difference of $T_{evap}^{min} = 2°\text{C}$ at the evaporator is now applied [65]. The evaporators now have an exit temperature of $T_{evap} = 6°\text{C}$, which is based on the heat source outlet temperatures of district cooling systems [107].

For the investment cost of the chiller, the same cost estimate as used for the heat pump is employed [108].

CO_2 Network

Next to the conventional technologies for heating and cooling, a CO_2 network is implemented in the superstructure as a more innovative solution, combining both heating and cooling services. The CO_2 network [108] consists of several decentralized units which can serve the users' heating and cooling demands, of pipes delivering the heat transfer fluid being CO_2, as well as of a central plant required for balancing the CO_2 network and for exchanging heat with the environment. The latter, both being a heat source and sink, could for example be a river, lake or sea such as for the heat pumps previously discussed. A simple overview of the CO_2 network units implemented in the superstructure can be seen in Figure 8.

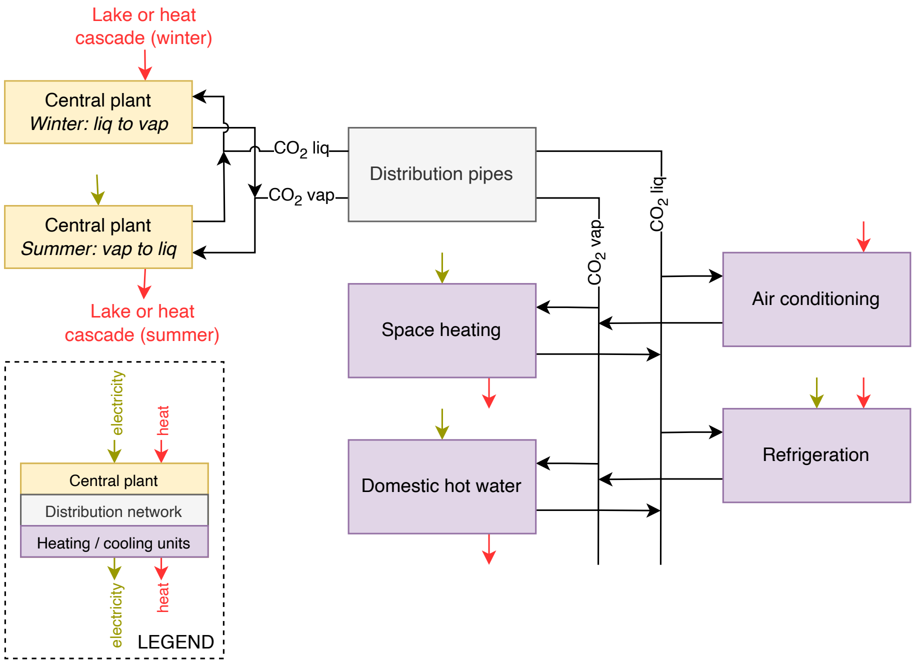


Figure 8: Overall structure of the CO_2 network (inspired from [109])

The CO_2 network uses CO_2 as a refrigerant transporting heat from the central plant throughout the network [109]. It is based on the latent heat of evaporation and condensation of CO_2. The working principle is described in [110]. When running in heating mode, the CO_2 is arriving in liquid form at the central plant where it is evaporated and compressed, in order to leave again as CO_2 vapour to the energy user units. In the cooling mode, the CO_2 arrives as vapour at the central plant where it is condensed with a pump and leaves again as liquid CO_2. Two pipes connect the central plant to the decentralized heating and cooling units, one for liquid and one for vaporized CO_2. The heating units for space heating and domestic hot water consist of a heat pump, which takes the heat from the vaporized CO_2 and makes it condense. The air conditioning unit uses a heat exchanger in which the CO_2 is evaporated with heat exchanged from the building. As the pipe with liquid CO_2 has a slightly higher pressure than the pipe with vaporized CO_2, no heat pump is needed here. For refrigeration cooling demands however, a heat pump again is needed for ensuring the cooling demands by vaporizing the CO_2.

The costs for the different units, namely the heat exchanger and heat pump at the central plant, the CO_2 pipes connecting the whole network and the distributed heat pumps (heating, refrigeration) and heat exchangers (air conditioning) around the building, are used from [108]. Furthermore, building data from OpenStreetMap [74] is used to estimate the required length for the pipes, which need to supply every part of the building with two pipes.

3.3.4 Hydrogen Technologies

Hydrogen is implemented as an electricity storage medium, no demand of hydrogen is included in the superstructure. In order to serve as an electricity storage medium, water needs to be converted with electricity to hydrogen, stored and then converted back from hydrogen, while producing electricity. Three units are implemented for electrolysis from water and electricity to oxygen and storable hydrogen: A solid oxide electrolyser cell, a proton-exchange membrane and an alkaline electrolyser cell. For storage, a pressurized compressed hydrogen tank is included. Finally, generation of electricity from the stored hydrogen can be done using a solid oxide fuel cell. An overview of the implemented technologies can be seen in Figure 9.

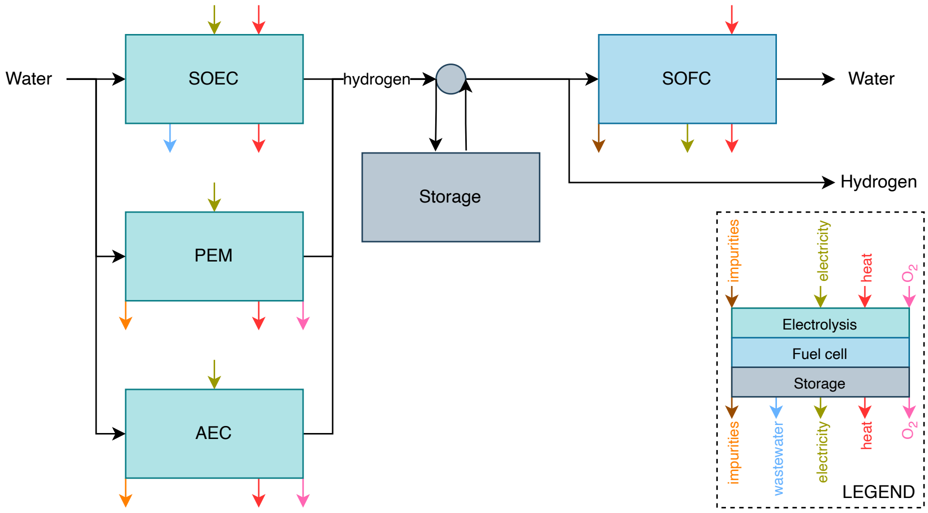


Figure 9: Overall structure of the implemented hydrogen storage system

Electrolysers

Three types of electrolyser are implemented for the production of hydrogen. Their models are based on the conversion efficiency, which is next to the cost the main difference of the different technologies. The models all consume water and electricity and produce oxygen, hydrogen and heat, some of them however also having other side products visible in Figure 9. The model for the alkaline electrolyser has the lowest efficiency of 73% [111] but appears to be the cheapest of the implemented electrolysis technologies [100]. The Proton-exchange membrane model has a medium efficiency of 82% [112] and also a significantly higher cost [100]. Finally, the solid oxide electrolyser cell has both the highest efficiency of 89% [113] but also a high cost [114].

Fuel Cell

The model of the solid oxide fuel cell is the reverse option of solid oxide electrolyser cells, both being two types of solid oxide cells. The models of these two technologies have been developed by colleagues at the IPESE lab [115]. The model of the solid oxide fuel cell displays an efficiency of 57%. Costs for this technology are obtained from [116].

Pressurized Hydrogen Storage

Hydrogen storage is ensured in the superstructure using a pressurized hydrogen storage tank. Out of different overground hydrogen technologies, such as also liquid cryogenic hydrogen storage or metal hydrides, pressurised hydrogen tanks have the lowest investment costs [100]. Only underground hydrogen storage has a slightly lower investment cost [100]. Next to the battery, hydrogen storage is included in the superstructure as a long-term seasonal energy storage method. The implemented pressurised hydrogen storage has a storage efficiency of 88% [100].

3.3.5 Synthetic Fuel Production

Two pathways [117] are implemented for the production of synthetic fuels. The first option is producing synthetic fuels from captured CO_2 using co-electrolysis. The second option employs biomass as a resource to produce synthetic fuels using biogasification. They subsequently both employ a Fischer-Tropsch synthesis for transforming the syngas into synthetic fuels. Finally, a separation unit allows to obtain the product fuels. An overview of the different pathways can be seen in Figure 10, with the individual technologies being described more in detail as follows. The costs of the different technologies are drawn from [100], [118]–[120].

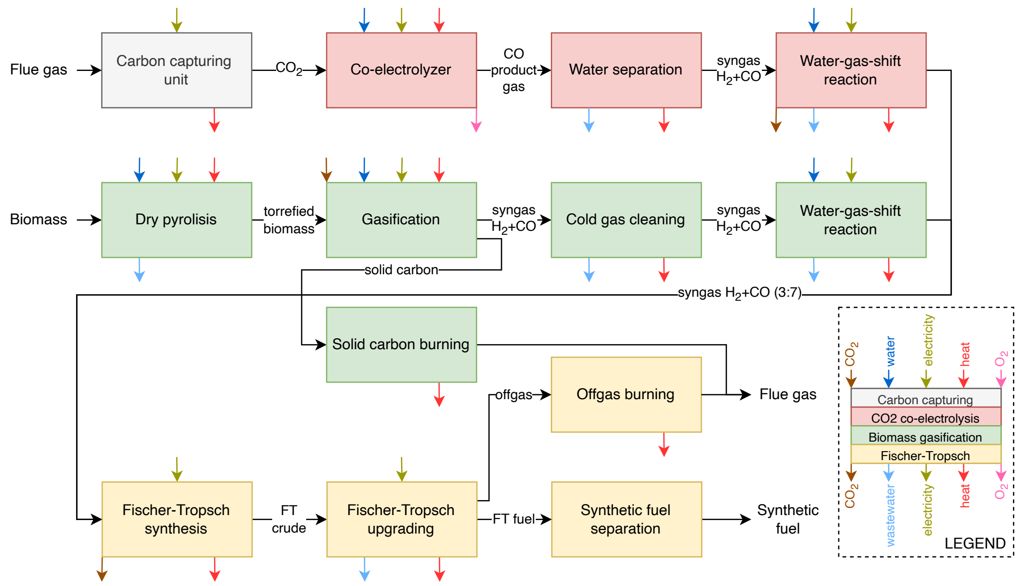


Figure 10: Overall structure of the implemented technology models for the production of synthetic fuels

Carbon Capturing

Different technologies exist for carbon capturing at different stages of development, which are mainly the following four: pre-combustion carbon capture, post-combustion carbon capture, oxyfuel combustion and direct air capture [121]. Direct air capture using adsorption has been developed significantly over the last year, but further technology developments are still needed in order to be deployed at large scale [122]. Overall, absorption-based technologies are currently still cheaper [100] and are thus used in this study. They can be used as post-combustion technologies for high-carbon industries and are the basis for the model implemented [123], [124]. This monoethanolamide carbon capture can for example be installed to capture emissions of the cement or steel industry [117] and could for example use fumes from the steel production site of Tata Steel in Ijmuiden [96]. For the future, it might be interesting to look into different technologies of carbon capture, as also direct-air capture from the ventilation system.

CO_2 Co-Electrolysis

The captured CO_2 can be used in the co-electrolysis model in the superstructure to produce synthesis gas [117]. In a first step, co-electrolysis uses CO_2 and water in the form of steam and the addition of heat to produce a synthesis product gas [125]. From this gas, water contents need to be separated in a subsequent water separation step. Finally, the optimal ratio of H_2 and CO needs to be obtained using a water-gas-shift reaction, which allows the synthesis gas to be forwarded to the Fischer-Tropsch synthesis [117].

Biogasification

The model of the biogasification pathway [119] starts with drying the biomass and torrefaction, which allows to upgrade the biomass product, to produce high-quality solid biomass products and thus in the end to improve the usage of the biomass in the subsequent gasification step [126]. Gasification subsequently allows to transform the biomass at very high temperatures into syngas, which is a composition of hydrogen, carbon monoxide, methane and carbon dioxide. The syngas can then be treated using cold gas cleaning, in order to remove for example tar, metal or sulfur impurities. Furthermore, its composition can be changed using a water-gas shift reaction for obtaining the optimal ratio of H_2 and CO for the Fischer Tropsch synthesis. The solid carbon produced from biogasification and other side products can be burnt and the heat can be reused within the biogasification process [125].

Fischer-Tropsch

The synthesis gas obtained from both co-electrolysis and biogasification needs to be further processed in order to obtain Fischer-Tropsch fuels, which are a mixture of straight-chain hydrocarbons similar to semi-refined crude oil [119]. They are obtained from the syngas using a catalytic non-selective exothermal reaction [119]. The crude Fischer-Tropsch fuels obtained still need to be upgraded in order to obtain the desired fuel products, such as for example kerosene, jet fuels or diesel [119]. Side product gases which are obtained throughout the process can be burnt to produce heat for the whole process, similar to what is done with the solid biomass obtained from gasification.

Synthetic Fuel Separation

Finally, the synthetic fuels need to be processed in refineries, where the Fischer-Tropsch crude fuel can be separated for example in sustainable aviation fuel. Average values for the investment costs of syncrude refineries have been used in this study [120]. While the heat streams have been neglected for the synthetic fuel separation unit, a simple model is constructed based on the possible output fuel composition estimated in the models of the AIDRES project [117], which is shown in Table 3. It can be seen that the share of kerosene and thus sustainable aviation fuel is quite low for this type of refinery. Refineries capable of generating more than 50% of kerosene are possible [127], their model implementation is however out of the scope of this study. It is recommended to look into this topic in future projects.

In this study, a simple estimation is made for the possible profit from synthetic fuel production based on the prices without taxes for the different fuel types in the Netherlands [128], [129]. For the light distillate fuels, the heavy reformates and isomerates, the price of gasoline is assumed, as they can often be blended with gasoline, as observable for typical refineries [130]. The prices assumed can also be found in Table 3.

Table 3: Output fuels from synthetic fuel production with estimated fuel share [117] and estimated prices [128], [129]

Fuel type	**Assumed fuel share in output synthetic fuel** [%]	**Assumed prices** [**EUR/l**]
Gasoline	11	0.81
Light distillate fuel	3	0.81
Gas oil	69	0.91
Kerosene	1	0.55
Heavy reformate	6	0.81
Isomerate	8	0.81
Fuel oil	2	0.64

3.3.6 Costs and Environmental Impact of Implemented Technologies

For all technologies explained in the previous subsections, a cost and an environmental impact are defined. The cost is composed of an annual investment cost (Cinv1), an annualised specific investment cost per reference unit size (Cinv2) and a variable operating cost per reference unit size (Cop2). The investment costs are in general annualised for an interest rate of 6% and a lifetime of 25 years. The impact is defined as the variable scope-2 GWP per reference unit size (Impact2). Table 4 gives an overview of the costs and the environmental impact for all technologies, which are compiled on the basis of the costs and impacts collected from multiple references.

3.4 OSMOSE Optimisation Framework

The energy system is optimised using the OSMOSE energy system integration framework which has been developed at the Industrial Process and Energy Systems Engineering (IPESE, formerly LENI) group of EPFL [35]. The mixed integer linear programming problem, the technology, resource and demand units as well as the optimisation framework are defined using the Lua programming language. The full energy system is modelled as a mathematical optimisation problem using AMPL and is solved using CPLEX. The optimisation framework ensures resource balance, process integration and correct sizing of the units [131]. Process integration is achieved using a heat cascade approach, allowing to obtain the minimum energy requirement [132].

The optimisation framework of OSMOSE [35] including the sets, the method for defining a unit and the main constraints will be explained based on and adapted from [131]. Several sets are employed in the optimisation, with the main ones listed as follows.

- $\boldsymbol{U}$: set of all units defining the technology models in the superstructure, with one model possibly containing several units
- $\boldsymbol{L}$: set of all layers connecting the units in the superstructure (for example electricity, natural gas or water)
- $\boldsymbol{P}$: set of all periods occurring recurrently over the year, with one period being equivalent to a typical day in this study

Table 4: Overview of costs and environmental impacts defined for different technologies in energy system after annualisation

Technology		Reference unit	Reference stream	**Cinv1** ($C_u^{inv,1}$) [€/y]	**Cinv2** ($C_u^{inv,2}$) [€/ref/y]	**Cop2** ($C_u^{op,1}$) [10^{-3}€/ref]	**Impact2** ($G_u^{op,1}$) [kgCO_2eq/ref]	Reference costs and impact
PV		m^2	solar cell area	0	7.09	0	0	[100]
Mini wind turbine		-	number wind turbines	0	3,396.92	0	0	[103]
Battery		kWh	electricity stored	0	31.49	0	0	[104]
Boiler natural gas		kW	heat produced	0	11.92	0.44	0.21	[100], [105], [106]
Combined cycle natural gas		kW	electricity produced	0	63.02	2.31	0.39	[100], [105], [106]
Heat pump		kW	electricity used	444.33	97.00	0	0	[108]
Chiller		kW	electricity used	444.33	97.00	0	0	[108]
CO_2 network	Heat pump	kW	electricity used	444.33	97.00	0	0	[108]
	Heat exchanger	kW	heat exchanged	15.89	4.14	0	0	[108]
	Piping	m	length pipes and excavation	133.77	0	0	0	[108]
Alkaline electrolyzer		kW	electricity required	0	135.37	0	0	[100]
Proton-exchange membrane		kW	electricity required	0	173.68	0	0	[100]
Solid oxyde electrolyzer cell		kW	electricity required	0	171.48	0	0	[114]
Solid oxyde fuel cell		kW	electricity produced	0	188.69	0	0	[116]
Pressurized hydrogen storage		kWh	H_2 stored	0	0.47	0.60	0	[100]
Carbon capturing		kg/h	CO_2 captured	0	$\sim$ 5,518.80	0	0	[100]
Co-electrolysis	Co-electrolyser	kg/h	CO_2 entering	0	731.31	0	0	[118]
	Water-gas shift	kg/h	syngas (H_2+CO) entering	380,399.42	199.85	0	0	[119]
Biogasification	Dry pyrolysis	kg/h	biomass entering	34,760.98	102.36	0	0	[119]
	Gasification	kg/h	torrefied biomass entering	10,841.05	15.11	0	0	[119]
	Cold gas cleaning	kg/h	syngas (H_2+CO) entering	12,591.06	4.67	0	0	[119]
	Water-gas shift	kg/h	syngas (H_2+CO) entering	380,399.42	199.85	0	0	[119]
	Solid carbon burn.	kg/h	solid carbon entering	195.20	0.01	0	0	[119]
Fischer-Tropsch Synthesis		kg/h	Fischer Tropsch fuel leaving	0	463.43	0	0	[133]
Synthetic fuel separation		kg/h	Fischer Tropsch fuel entering	0	311.73	0	0	[120]

- $\boldsymbol{T}(p)$: set of all time instances in period p with distinct input data, with one time interval being one hour in this study
- $\boldsymbol{TS}(p,t)$: set of all streams at time instance t in period p, including a number of n_s resource streams (with the resource stream being associated to a layer), n_{ut} utility streams and n_{pr} process streams (with the latter two being part of the heat cascade)

Every technology unit u in U is defined with a set of state variables. First, all units have a minimum load f_{min_u} and a maximum load f_{max_u}, with $f = 1$ being the reference load of the unit. All units have a set of streams s going in and out of the unit. The resource streams are defined using the layer l they are belonging to as well as the quantity going in or out of the unit. The heat streams are defined using the enthalpy they exchange, the inlet and outlet temperature and the minimum temperature difference to the supplying or receiving heat streams.

Moreover, the units have investment and operating costs as well as a GWP assigned to them. The following cost parameters are being used for every unit u.

- $C_u^{inv,1}$ [€/y]: annualized fixed investment costs
- $C_u^{inv,2}$ [€/ref/y]: annualized specific investment costs per reference load
- $C_u^{op,1}$ [€/ref]: variable operating costs per reference load
- $G_u^{op,1}$ [kgCO_2eq/ref]: variable GWP per reference load

Multiple decision variables are used for scaling the different units as well as their connections. The most important decision variables, which are used in the main constraints, are listed as follows.

- f: load of the the different units, which is defined for each time as well as for the maximum load installed
- y: binary value defining presence of the unit in the energy system configuration
- rs: size of resource stream exchanged between two units
- q: heat exchanged by a utility or process unit within the heat cascade
- hc: heat cascaded at different temperature intervals in the heat cascade

The sets and decision variables together with the state variables defined in all technology models are used in a diverse set of constraints. The main constraints employed for optimising the energy system are the following (taken and adapted from [131]). Equation 17 is used for dimensioning of the technology. It is complemented with Equation 18 and Equation 19 constraining unit size and presence.

$$F_{min_u} \cdot y_{u,p,t} \leq f_{u,p,t} \leq F_{max_u} \cdot y_{u,p,t} \qquad \forall t \in \boldsymbol{T}(p), \quad \forall p \in \boldsymbol{T}, \quad \forall u \in \boldsymbol{U} \tag{17}$$

$$f_{u,p,t} \leq f_u \qquad \forall t \in \boldsymbol{T}(p), \quad \forall p \in \boldsymbol{P}, \quad \forall u \in \boldsymbol{U} \tag{18}$$

$$y_{u,p,t} \leq y_u \qquad \forall t \in \boldsymbol{T}(p), \quad \forall p \in \boldsymbol{P}, \quad \forall u \in \boldsymbol{U} \tag{19}$$

At every instance of time t within period p, the load $f_{u,p,t}$ of the unit u must be in the range between its minimum load F_{min_u} and its maximum load F_{max_u}. If the binary value $y_{u,p,t}$ defining if the unit is present is equal to zero, the load of the unit is also constrained to zero. Furthermore, at any instance of time, the load $f_{u,p,t}$ must be smaller than the maximum load f_u of the optimised configuration. The same applies to the presence of the unit y_u in the optimised configuration.

Furthermore, Equation 20 ensures the balance of the resources, which can for example be electricity ($\dot{e}$) or natural gas ($\dot{h}$).

$$\sum_{s=1}^{n_s(l)} rs_{in_{s,p,t}} = \sum_{s=1}^{n_s(l)} rs_{out_{s,p,t}} \qquad \forall t \in \boldsymbol{T}(p), \quad \forall p \in \boldsymbol{P}, \quad \forall l \in \boldsymbol{L} \tag{20}$$

At every time t in period p, the resources rs going in must be equal to the resources going out of the system. This balance is ensured by summing up all streams s within a layer l.

Next to the resource streams, also the balance of the heat streams needs to be ensured, which is done using the heat cascade constraint in Equation 21 as well as complementing the constraints shown in Equation 22.

$$\sum_{w=1}^{n_{ut}} f_{w,p,t} q_{ut_{w,p,t,r}} + \sum_{i=1}^{n_{pr}} q_{pr_{i,p,t,r}} + hc_{p,t,r+1} - hc_{p,t,r} = 0 \qquad \forall r = 1,...,n_{hc}, \quad \forall t \in \boldsymbol{T}(p), \quad \forall p \in \boldsymbol{P} \tag{21}$$

$$hc_{p,t,1} = 0 \quad ; \quad hc_{p,t,n_r+1} = 0 \quad ; \quad hc_{p,t,r} \geq 0 \qquad \forall r = 1,...,n_{hc}, \quad \forall t \in \boldsymbol{T}(p), \quad \forall p \in \boldsymbol{P} \tag{22}$$

The heat cascade constraint ensures at any instance of time t in period p the balance of heat for all n_r temperature intervals r. Within each interval r, the heating or cooling flow $q_{ut_{w,p,t,r}}$ from all the utility units w with load $f_{w,p,t}$ is added to the heat exchanged by the streams $q_{pr_{i,p,t,r}}$ of all processes i, including the fixed heat demands. The balance is closed with heat $hc_{p,t,r+1}$ which is cascaded from higher temperature intervals $r+1$ and heat $hc_{p,t,r}$ from lower intervals r. Moreover, it is ensured that no heat can be cascaded for the lowest and highest temperature interval and that any heat cascaded must be larger than or equal to zero.

When including storage units in the optimisation, additional sets and constraints are used (reproduced from the constraints implemented in OSMOSE [35]). The following adapted sets are needed for units and time instances.

- $\boldsymbol{U}_s$: set of all storage units implemented in the superstructure
- $\boldsymbol{T}_r$: set of all time instances from correctly sorted and repeating periods during the full year (one typical day can occur multiple times in a year, meaning that every time instance occurring once in T can occur for multiple days in T_r)

Furthermore, the subsequent additional decision variables are needed for an optimisation including storage units.

- es_{level}: energy storage level of storage unit at the end of time instance
- $es_{in/out}$: in- and outgoing energy to and from the storage unit

The main constraint for implementing long-term storage units in OSMOSE is shown in Equation 23.

$$es_{level_{u_s,t_r}} = \begin{cases} \sigma_{u_s} \cdot es_{level_{u_s,-1}} + es_{in_{u_s,t}} - es_{out_{u_s,t}} & if\ t_r = 0 \\ \sigma_{u_s} \cdot es_{level_{u_s,t_r-1}} + es_{in_{u_s,t}} - es_{out_{u_s,t}} & if\ t_r \neq 0 \end{cases} \qquad \forall t_r \in \boldsymbol{T}_r, \quad \forall u_s \in \boldsymbol{U}_s \tag{23}$$

This storage constraint ensures that for every storage unit u_s, the storage level $es_{level_{u_s,t_r}}$ at the end of time instance t_r within the full year is equal to the streams $es_{in_{u_s,t}}$ and $es_{out_{u_s,t}}$ going in and out of the storage unit during this time instance and the storage level $es_{level_{u_s,t_r-1}}$ at the end of the previous time instance multiplied with the storage efficiency σ_{u_s}, indicating the losses from discharge during every time instance.

A diverse set of tests is applied to verify the functioning of the model, which confirms the unit implementations, working of the constraint definitions and correct computations of the systems' characteristics, such as the overall costs. An overview of the methods employed for verifying the optimisation framework is given in Appendix A.

3.5 Objective Functions

The implemented energy system model can be optimised for different objectives [34]: operating costs, capital investment costs, a combination of the latter two, or the GWP. The definitions (adapted from [34]) of these will be given in this section.

The first objective are the yearly operating costs YC^{op}, for which the objective function is shown in Equation 24.

$$YC^{op} = \sum_{p \in \boldsymbol{P}} D_p \cdot \sum_{t \in \boldsymbol{T}(p)} \left(C^{el,+}_{p,t} \cdot \dot{e}^{gr,+}_{p,t} + C^{ng,+} \cdot \dot{h}^{gr,+}_{p,t} + \sum_{u \in \boldsymbol{U}} \left(C^{op,1}_{u} \cdot f_{u,p,t} \right) \right) \tag{24}$$

The operating costs are defined as the sum of the individual operating costs for all periods P, each with their respective hourly divisions $T(p)$. They are multiplied with the frequency of occurrence D_p of every period p. For each hour, the operating cost is composed of the grid electricity used $\dot{e}^{gr,+}_{p,t}$ multiplied with the price of grid electricity $C^{el,+}_{p,t}$ during that hour, the natural gas used $\dot{h}^{gr,+}_{p,t}$ multiplied with the price of natural gas $C^{ng,+}$ and the operating costs of the units. The operating costs of the units are calculated as the sum of the usage factor $f_{p,t,u}$ during every hour and the operating cost $C^{op,1}_{u}$ for all units U.

The annualised yearly investment costs YC^{cap} can be calculated from the overall investment costs YC^{inv} by annualizing them as shown in Equation 25. The overall investment costs are computed from Equation 26

$$YC^{cap} = \frac{ir \cdot (1 + ir)}{(1 + ir)^{lt} - 1} \cdot YC^{inv} \tag{25}$$

An interest rate of $ir = 6\%$ is in general used for this study, with an assumed lifetime of $lt = 25$years.

$$YC^{inv} = \sum_{u \in \boldsymbol{U}} \left(C_u^{inv,1} \cdot y_u + C_u^{inv,2} \cdot f_u \right) \tag{26}$$

The investment costs of all units U can be calculated from the sum of the fixed investment costs $C_u^{inv,1}$ multiplied with a binary variable y_u indicating the presence of the unit and the variable investment costs $C_u^{inv,2}$ multiplied with the usage factor of the unit.

Finally, Equation 27 for obtaining the yearly GWP YG^{op} of the energy system looks very similar to the equation for the operating costs. For the emissions, it must be noted that in this study only scope-1 and -2 emissions are considered. These are emissions directly generated from imported or produced energy resources on site (scope-1) or emissions released in the generation process of imported electricity (scope-2) [134]. Other upstream or downstream emissions (scope-3) are neglected in this study.

$$YG^{op} = \sum_{p \in \boldsymbol{P}} D_p \cdot \sum_{t \in \boldsymbol{T}(p)} \left(G_{p,t}^{el,+} \cdot \dot{e}_{p,t}^{gr,+} + G_{p,t}^{ng,+} \cdot \dot{h}_{p,t}^{gr,+} + \sum_{u \in \boldsymbol{U}} \left(G_u^{op,1} \cdot f_{u,p,t} \right) \right) \tag{27}$$

Now, $G_{p,t}^{el,+}$ are the emissions assigned to every kWh of electricity at any hour of the year, $G_{p,t}^{ng,+}$ the emissions assigned to every kWh of natural gas, and $G_u^{op,1}$ the direct on-site emissions from using unit u.

3.6 Key Performance Indicators

Different key performance indicators are used next to the objectives to assess the different energy system configurations obtained. First, the efficiency of the energy system is addressed. This is done using energy and exergy efficiency as can be seen in Equation 28 and Equation 29 [34].

$$\eta_{en} = \frac{En^{fuel,-} + E^{dem,-} + Q^{dem,-}}{En^{fuel,+} + E^{gr,+} + E^{ren,-}} \tag{28}$$

Energy efficiency η_{en} can be computed as the sum of the useful energy leaving the energy system, which are the fuels sold $En^{fuel,-}$, the electricity demand of the airport $E^{dem,-}$ and the heat demand of the buildings $Q^{dem,-}$, divided by the energy going in the energy system, being the sum of fuels $En^{fuel,+}$ and electricity $E^{gr,+}$ consumed by the energy system and renewable energy generated $E^{ren,-}$ on site.

$$\eta_{ex} = \frac{Ex^{fuel,-} + Ex^{dem,-} + Ex^{Q^{dem},-}}{Ex^{fuel,+} + Ex^{gr,+} + Ex^{ren,-}} \tag{29}$$

Exergy efficiency η_{ex} is computed in a similar way, now dividing the sum of the useful exergy leaving the system, which is composed of the exergy $Ex^{fuel,-}$ of the sold fuels, the exergy $Ex^{dem,-}$ of the electricity demand as well as the exergy $Ex^{Q^{dem},-}$ of the heating demand, divided by the exergy entering the system, being the sum of the exergy $Ex^{fuel,+}$ of the fuels used, the exergy $Ex^{gr,+}$ of electricity from the grid and the exergy $Ex^{ren,-}$ of the renewable electricity generated at the airport.

Energy and exergy efficiency can be computed both including or excluding the efficiency of the local renewable electricity production methods. For the PV, the energy upstream of them is computed by multiplying their area with the solar irradiation [34]. The exergy per square meter upstream of the solar cells is computed using the following Equation 30 [135].

$$Ex_{irr} = I \cdot \left(1 - \frac{4}{3}\frac{T_0}{T} + \frac{1}{3}\left(\frac{T_0}{T}\right)^4 \right) \tag{30}$$

Where I is the solar radiation, T_0 is the temperature of the environment and T the temperature of the sun.

For the wind energy, the exergy and the energy upstream of the wind turbine are computed using the following Equation 31 [136], which determines the amount of energy available across the swept area of the wind turbine, and which is equivalent to Equation 15 without the efficiency of the wind turbine.

$$Ex_{wt} = \frac{1}{2} \cdot A_{sw} \cdot \rho_{air} \cdot {v_t}^3 \tag{31}$$

Next, self-sufficiency of the energy system in terms of electricity consumption can be looked at, which is defined as can be seen in Equation 32 [34]. It indicates how much of the electricity demand of the airport is fulfilled with electricity generated at the airport.

$$SS = \frac{E^{loc,+} - E^{gr,-}}{E^{loc,+} + E^{gr,+} - E^{gr,-}} \tag{32}$$

Where $E^{loc,+}$ is electricity locally produced at the airport.

Finally, the renewable electricity share can be looked at, as displayed in Equation 33 [34]. This indicator allows to see how much of the electricity consumed at the airport is renewable electricity.

$$RES = \frac{\sum_{p \in \boldsymbol{P}} \sum_{t \in \boldsymbol{T}(p)} \dot{e}_t^{gr,+} \cdot (\epsilon_t^{gr,ren}) + E^{loc,ren,+}}{E^{gr,+} + E^{loc,+}} \tag{33}$$

In this indicator, both the electricity generated on site as well as the electricity imported from the grid is looked at. For the locally produced electricity, the amount of renewable locally produced electricity $E^{loc,ren,+}$ is included. For the electricity coming from the grid, the share of renewable electricity $\epsilon_t^{gr,ren}$ at every hour in the year is included.

4 Energy Demand Estimation

Having described the full methodology, this section presents the case study airports to which the energy demand estimation and system optimisation will be applied. The main airport, on which the analysis is based, is Amsterdam Schiphol airport, for which the input data is shwon in section 4.1 and the estimated energy demand is displayed in section 4.2. Next, section 4.3 explains which other European hub airports are chosen to test the model. Finally, section 4.4 depicts the typical days constructed from the estimated energy demand.

4.1 Input Data Amsterdam Schiphol

The main case study looked at in this study is on Amsterdam Schiphol airport, the largest airport of the Netherlands. It welcomes more than 60 million passengers every year and operates more than 400,000 air traffic movements per year [137]. The airport is used as the main hub of the largest Dutch airline, KLM [138]. An overview of the main figures of Amsterdam Schiphol airport can be seen in Table 5.

Table 5: Airport characteristics of Amsterdam Schiphol airport

Airport characteristic	Value	Reference
Building surface area $[m^2]$	253,481.1	computed from [74] data
Building wall length $[m]$	11,543.0	computed from [74] data
Number of passengers in 2023 [-]	61,885,367	[87]
Number of flights in 2023 [-]	460,035	[86]

A surface area of more than 250,000m^2 is estimated using data from [74]. They are distributed over 8 piers and 3 terminals, which are displayed in red in Figure 11. The other buildings, coloured in black on the map, are excluded from the analysis, as is explained in section 3.1.

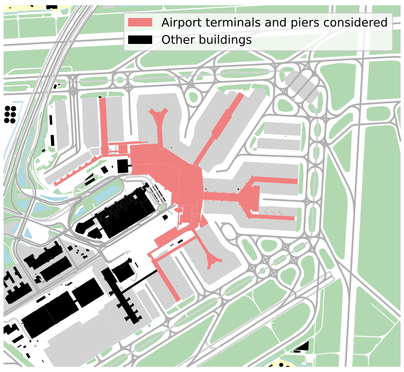
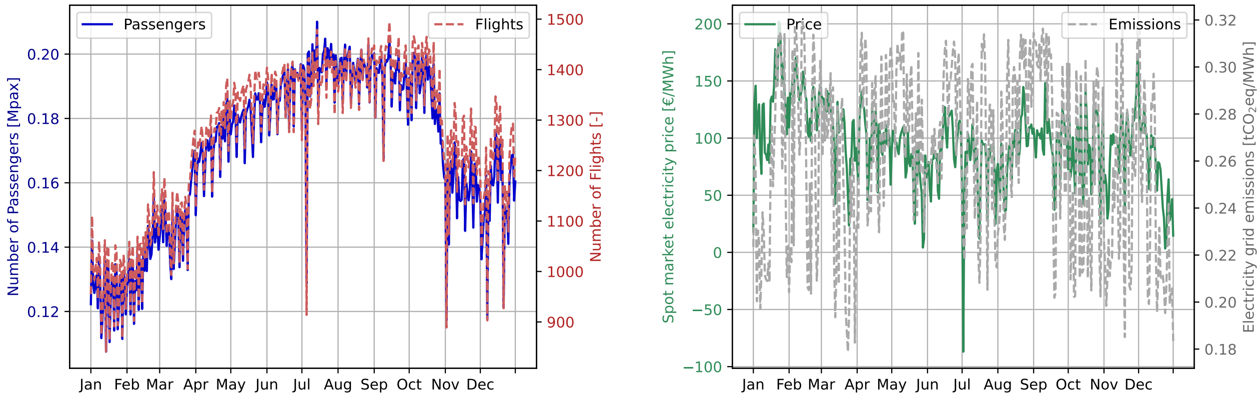


Figure 11: Map of considered terminal and pier buildings at Amsterdam Schiphol airport (using data from [74])

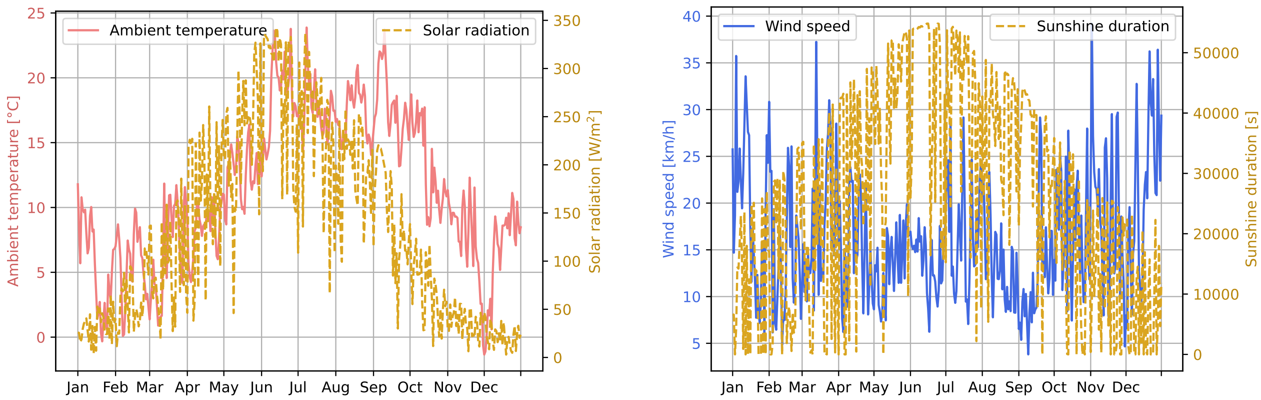
As described in section 3.2, different input data needs to be collected before determining the energy demand and optimising the airport's energy system. The number of flights and the estimated number of passengers over the year of 2023 can be seen in Subfigure 12(a). Next, Subfigure 12(b) shows the variation of the electricity price as well as the estimated emissions per kWh of electricity in 2023 in the Netherlands.



(a) (b)

Figure 12: Characteristics of case study of Amsterdam Schiphol airport in 2023: (a) number of flights [86] and passengers (monthly passenger numbers from [87]) and (b) electricity price [90] and emissions (average yearly emissions per kWh from [91], yearly profile of renewable energy share from [90]) in the Netherlands

Furthermore, weather data needed to be obtained. Figure 13 shows the profile of the temperature, solar radiation, wind speed and sunshine duration in 2023 at Amsterdam Schiphol airport.



(a) (b)

Figure 13: Weather data at Amsterdam Schiphol airport in 2023 [88]: (a) temperature and solar radiation and (b) wind speed and sunshine duration

4.2 Energy Demand Amsterdam Schiphol

With the input demand from section 4.1 as well as the methods described in section 3.1, the energy demand profile for Amsterdam Schiphol airport for the case study year 2023 can be determined. Figure 14 shows an overview of the weekly moving average of the input energy demand which is used for optimising the airport's energy system. For the heating and cooling demand, clear seasonal variations can be seen, with the heating needs being higher during winter and the cooling needs during summer. The electricity and vehicle energy demand are more constant over the full year, as they are less dependent on the weather and more on the number of passengers and flights. The vehicles make up around 10% of the overall energy demand. The smallest demand is the domestic hot water demand, which is added to the heating demand of the buildings.

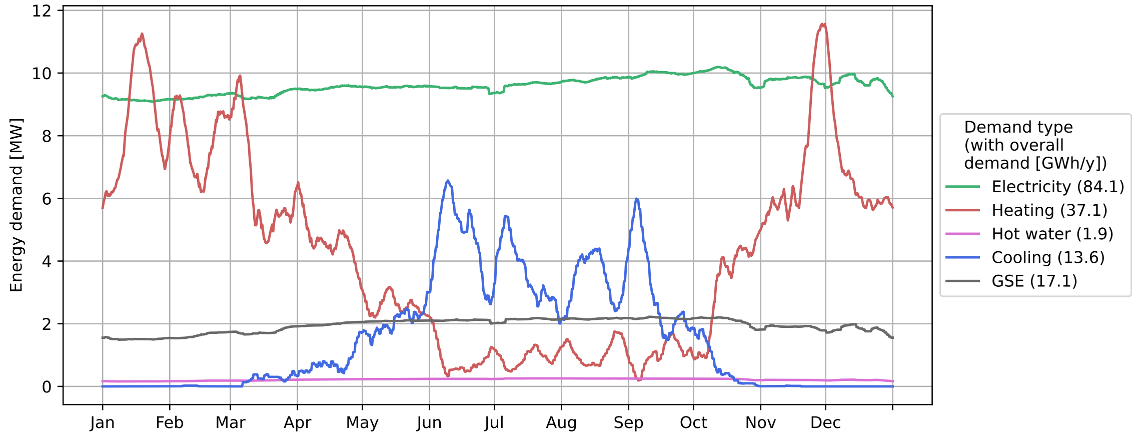


Figure 14: Weekly moving average of the estimated input energy demand for Amsterdam Schiphol airport

The data for the vehicle as well as building electricity demand has been determined based on known values for the year of 2023. The energy demand of the heating, ventilation and cooling system has however been estimated based on the building envelope. The values obtained can be compared to actual energy consumption data of Amsterdam Schiphol airport for the year of 2023 [71], which is done in Table 6. It can be seen that the heating, ventilation and cooling demand are all within less than 15% of the approximated demands from the statistics. Only the estimated domestic hot water appears to be 24% lower than the approximated real airport demand. However, its value being an order of magnitude smaller than the overall heating demand, this difference can be neglected. Thus, the energy demand model results obtained can be validated for the case of Amsterdam Schiphol airport.

Table 6: HVAC system comparison model results and estimate based on real airport data [71]

HVAC consumer	**Model results energy demand [GWh]**	**Estimated real airport data energy consumption [GWh]**
Heating	37.1	37.6
Cooling	13.6	12.0
Domestic hot water	1.9	2.5
Ventilation	30.5	26.2

4.3 Estimated Energy Demand European Hub Airports

As the energy demand model is a universal model applicable to different airports when knowing the number of flights and passengers, the building characteristics as well as weather data, the model is also applied to other airports than Amsterdam Schiphol. In consequence five other major European hub airports from different climate zones are chosen. The selection of case study airports can be seen on Figure 15.

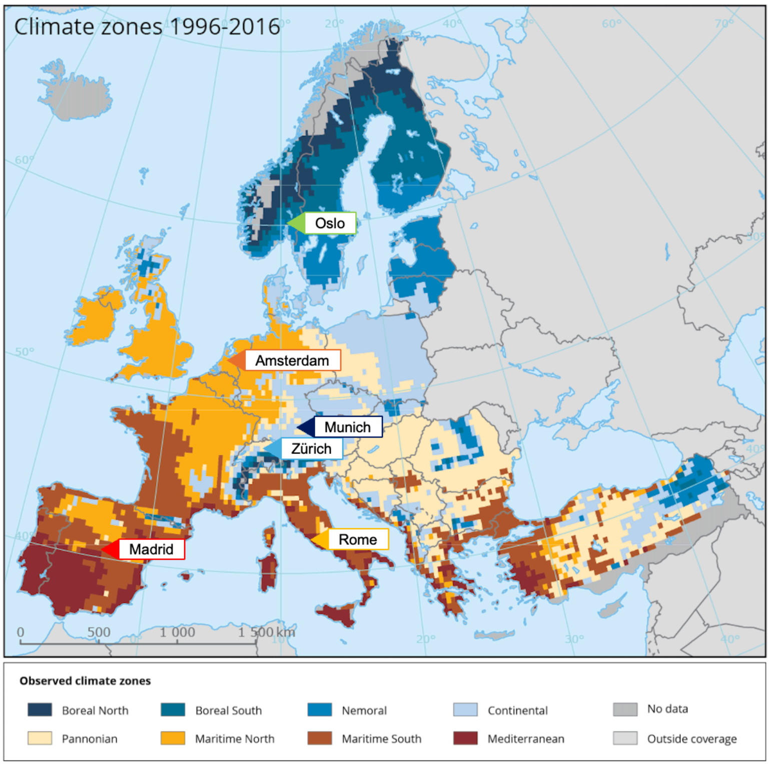


Figure 15: Map with the locations of the case-study airports and their respective climate zone (adapted from [139], [140])

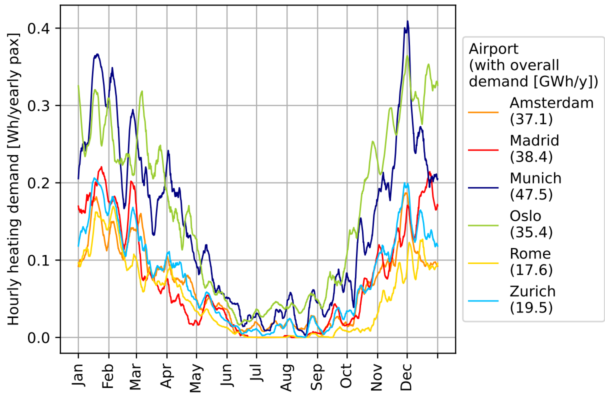
Including Amsterdam Schiphol, the six airports chosen represent well the different climate zones [139] existing in Europe. Madrid and Rome have a warm Mediterranean climate with mild winters and hot summers, with Madrid also having a minor maritime influence. Munich and Zurich lie in central Europe characterised by a continental and more stable climate, with Zurich also having a slight alpine climate influence. Amsterdam is located in the Northern maritime climate zone with varying weather conditions. Finally, Oslo represents the Northern part of Europe with a southern boreal climate, having colder winters than the other locations.

The airport characteristics, including the building sizes as well as the number of flights and passengers, can be found in Table 7. Additional input data, including the airport map with the considered buildings as well as the flight, passenger, weather, electricity and energy demand profiles for all airports, are provided in Appendix B. Whilst all airports have a comparable magnitude, it should be noted that Amsterdam and Madrid are the largest airports of this sample, both having more than 60 million passengers per year. On the other hand, Oslo and Zurich are the smallest two airports with 25 to 30 million passengers per year. When computing the relative sizes, it can be observed that the number of passengers per m^2 range from 154 at Munich airport to 252 at Zurich, having an influence on the determined energy demand. Next to that, the average number of passengers per flight ranges from 117 in Zurich to 158 in Madrid.

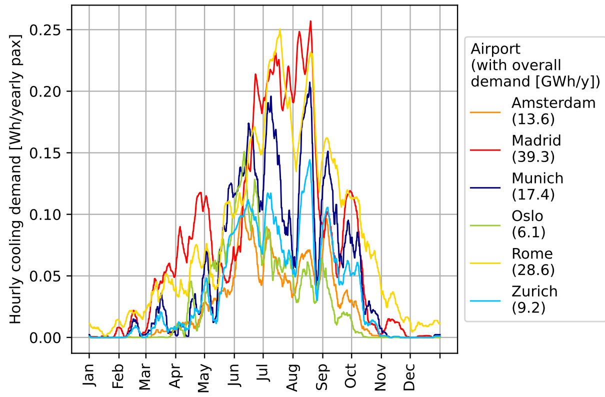
Table 7: Airport characteristics in 2023 for airports chosen as case studies: building surface area [74], building wall length [74], number of passengers [87], [141]–[145] and number of flights [86]

Airport	**ICAO code**	**Building surface area** $[m^2]$	**Building wall length** $[m]$	**Number of passengers** $[10^6]$	**Number of flights** $[10^3]$
Amsterdam Schiphol	EHAM	253,481.1	11,543.0	61.9	460.0
Madrid-Barajas	LEMD	370,226.4	12,561.9	60.2	380.3
Munich	EDDM	240,035.6	14,373.8	37.0	296.9
Oslo-Gardermoen	ENGM	106,172.9	7,904.5	25.1	211.6
Rome-Fiumicino	LIRF	193,935.6	11,373.6	40.5	261.3
Zurich	LSZH	114,443.6	6,087.9	28.9	245.8

From the airport building, passenger, flight and weather characteristics, the energy demands for the different airports are again computed using the methods described in section 3.1. The resulting profiles can be seen in Figure 16.



(a)



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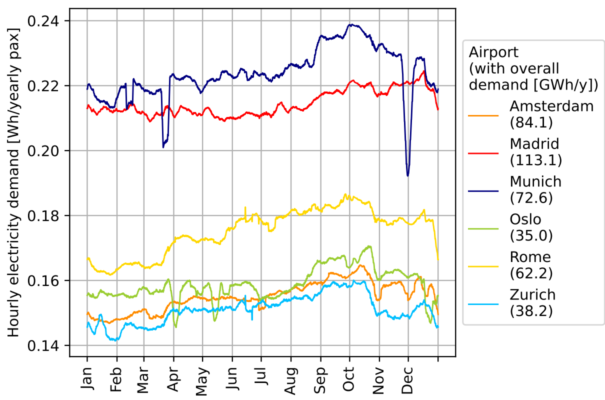
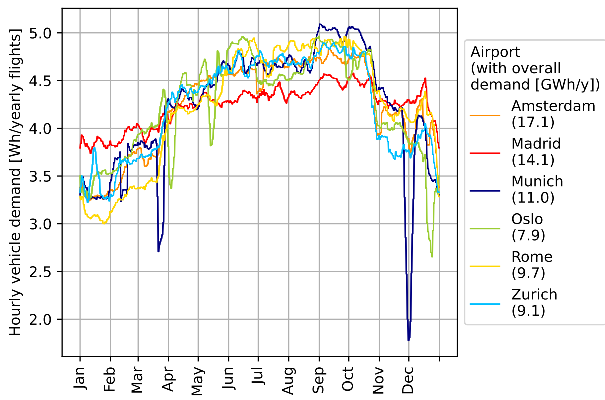


(c)



(d)

Figure 16: Comparison of energy demand for the different case study airports: (a) heating demand, (b) cooling demand, (c) eletricity demand and (d) vehicle energy demand

For the heating demand in Subfigure 16(a), it can be seen that Munich displays the highest value of 47.5GWh/y/pax per passenger, due to its continental climate and the large surface area per passenger. This large surface area per person is also the explanation why Madrid has a relatively high heating requirement per passenger of 38.4GWh/y/pax even whilst being located in a Mediterranean climate, whereas Zurich has a relatively low requirement per passenger of 19.5GWh/y/pax despite being located in an Alpine climate.

Looking at the cooling demand in Subfigure 16(b), as expected due to the Mediterranean climate a very high demand per passenger can be observed for Madrid and Rome with values of 39.3GWh/y/pax and 28.6GWh/y/pax respectively. Their cooling needs are particularly high during the spring and summer period. On the other hand, as expected the lowest values are observed for Zurich and Oslo with values of 9.2GWh/y/pax and 6.1GWh/y/pax, respectively.

For the electricity demands, the highest values are observed for Madrid, Amsterdam and Munich with values from 113.1GWh/y/pax to 72.6GWh/y/pax. It can be noted from Subfigure 16(c), that Munich has the highest per passenger electricity demand. Oslo and Zurich have the lowest values per passenger of 35.0GWh/y/pax and 38.2GWh/y/pax. It can be seen that the electricity demand is mostly influenced by the buildings surface area due to the large share of the ventilation requirements in the overall electricity demand, whereas heating and cooling requirements are mostly influence by the weather.

Finally, Subfigure 16(d) displays the vehicle energy demand. Similar profiles can be obtained, with Amsterdam having the largest overall requirement of 17.1GWh/y/pax and Oslo having the lowest requirement of 7.9GWh/y/pax. The values for the vehicle energy consumption fully depend on the number of flights, different to the previously mentioned demands influenced by the number of passengers.

To validate the model for the energy demands of other airports than Amsterdam Schiphol, the overall yearly demands are compared to overall yearly demands of European airports of similar sizes for the last years, which are obtained in the literature study. The comparison can be seen in Figure 17.

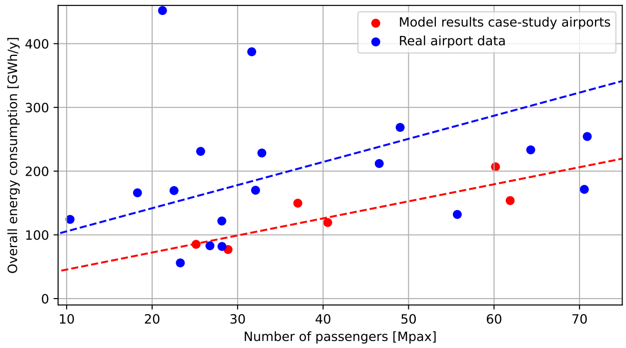


Figure 17: Comparison of overall airports energy consumption per passenger between model results and real airport data from [5], [10]–[32]

From the comparison with real European airport demand data, it can be concluded that the estimated values fall in the same range, but are comparable rather to the lower than to the higher airport energy demands. When drawing a trend line, it can be seen that the average model results are approximately 40% lower than the actual data points. Considering that the terminal building and airfield handling energy demand at Amsterdam Schiphol airport made up 61% of the overall airport demand, this deviation from the real airport data seems to confirm the correct working of the model. However, conclusions can only be drawn to a limited extent from this comparison, as airport demands or consumptions are published in slightly different ways for all airports. Thus, this comparison is not able to confirm precisely the estimated airport energy consumptions but can confirm results of correct magnitude for the energy demand model.

4.4 Typical Days

From the estimated energy demands, typical days are finally constructed in order to reduce the optimisation complexity, as is described in section 3.2.2. The resulting typical days, based on the temperature, solar irradiation and wind speed, can be seen in Figure 18. It can be observed that the typical days 1 to 6 are more winter days with low temperatures and irradiation, whereas days 7 to 12 represent summer days with high temperatures and radiation. Across both types of days, there are days with more and less average wind speed.

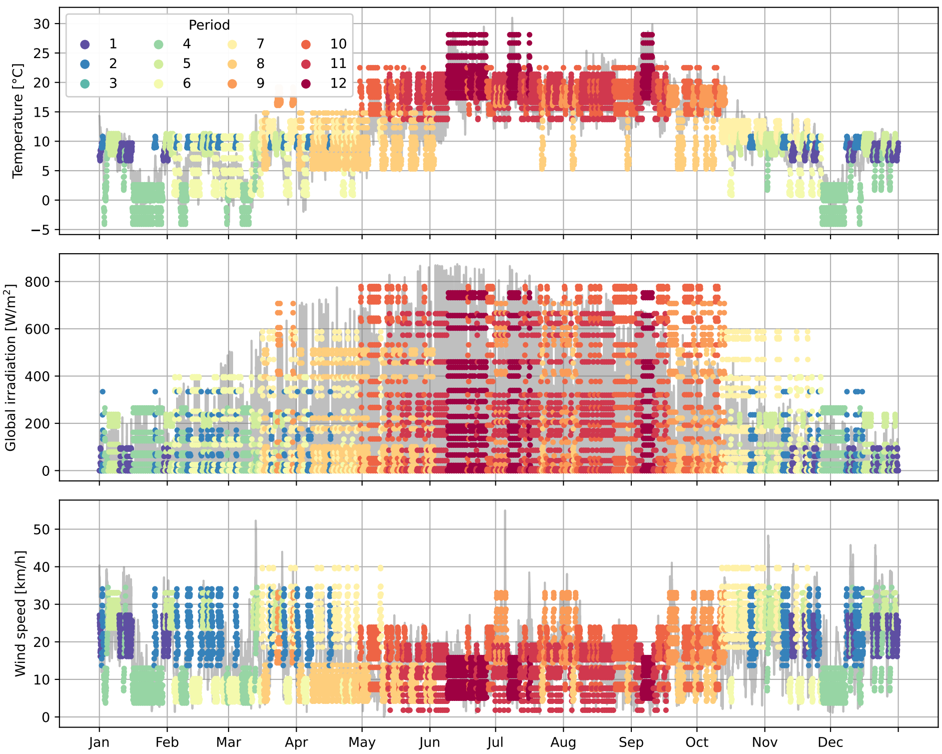


Figure 18: Clustering of the typical days for Amsterdam Schiphol airport

Figure 19 displays the range of temperature, solar radiation and wind speed covered by the typical days.

It can be observed that the typical days cover well all days but lack at the edges of the curves, where the highest and lowest values occur. Thus, it is important to include the extreme days in the analysis so that the technologies are correctly scaled to also produce sufficient energy during extreme days.

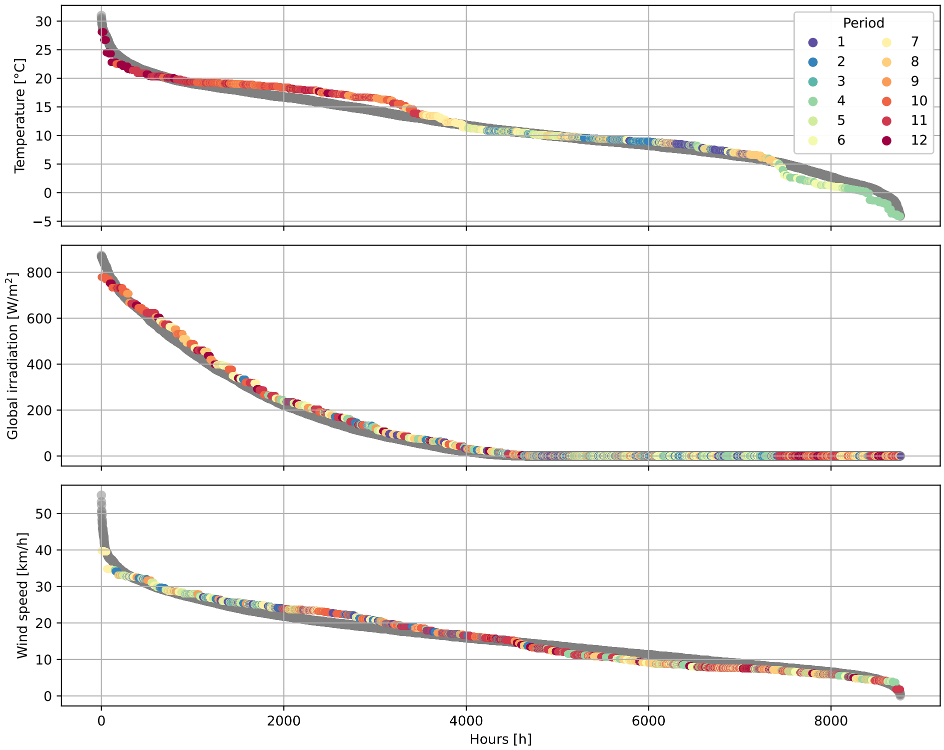


Figure 19: Clustering of the typical days for Amsterdam Schiphol airport

5 Optimisation Results

With the typical days obtained from the input energy data, the estimated energy demand shown in section 4 and the superstructure and optimisation framework described in section 3, the airport's energy system can be designed. First, the energy system will be optimised in section 5.1 for different scenarios for Amsterdam Schiphol. Next, the possibility of producing synthetic fuels is looked into in section 5.2. Finally, section 5.3 explores the option of applying the optimisation framework to other European hub airports.

5.1 Energy System Optimisation Amsterdam Schiphol

In a first step, the energy system for Amsterdam Schiphol is analysed and possible solutions are generated. First, a set of different solutions is generated using a Pareto analysis in section 5.1.1. Next, the different configurations observed are further analysed in section 5.1.2. The option of a completely independent energy system is looked into in section 5.1.3. Finally, section 5.1.4 displays the sensitivity of the optimal energy system on several technology investment costs.

5.1.1 Generation of Energy System Solutions for Different Scenarios

Different solutions of possible energy systems fulfilling the energy demands shown in Figure 14 need to be generated, allowing to observe possible technology configurations and to select specific solutions for further analysis. This is done using a Pareto analysis approach. This approach allows to generate distinct configurations performing optimal for different objectives. In this way, on the one hand results are obtained performing particularly well with maximal usage of the grid, while on the other hand configurations which produce more electricity on site are created. The range of results can then be studied and promising results can be selected for more detailed analysis. Six different scenarios are used for generating the Pareto curves, which differ by the type of energy storage technologies implemented. The six scenarios are the following:

- **No storage:** No storage technology implemented, all other technologies allowed to be used.
- **No storage, no natural gas:** No storage technology implemented, technologies employing natural gas (boiler, combined cycle) prohibited.

- **Battery:** Battery implemented as storage technology, all other non-storage technologies allowed to be used.
- **Battery, no natural gas:** Battery implemented as storage technology, technologies employing natural gas (boiler, combined cycle) prohibited.
- **Hydrogen:** Pressurised hydrogen tank together with electrolysis and fuel cell implemented as storage technology, all other non-storage technologies allowed to be used, no reduction in hydrogen technology costs.
- **Hydrogen, -50% costs:** Pressurised hydrogen tank together with electrolysis and fuel cell implemented as storage technology, all other non-storage technologies allowed to be used, 50% reduction in the hydrogen technology investment costs ($c_u^{inv,1}$ and $c_u^{inv,2}$).

The three base scenarios are the options of no storage, battery or hydrogen storage. For the scenario with no storage unit, it is furthermore investigated if not having any non-renewable resources would alter the optimisation results. As the battery is observed to be the more competitive storage technology, it is analysed how performance would change when not including non-renewable resources. For the hydrogen storage scenario, it is investigated whether a 50% reduction in the costs of the hydrogen related technologies (hydrogen tank, electrolysers, fuel cell) would improve competitiveness compared to the battery. It must be noted that the production of synthetic fuels is left out in those scenarios and will be looked at specifically in section 5.2.

For all of the scenarios, a six-point Pareto curve is constructed. The Pareto analysis is performed by optimising the total costs of the energy system with a varying weight on the annualised investment and operating costs, as shown in Equation 34.

$$Objective\ Function = \alpha^{inv} \cdot YC^{inv} + (1 - \alpha^{inv}) \cdot YC^{op} \tag{34}$$

Variation of the importance of investment and operating costs is obtained by altering the weight on the investment cost α^{inv} from 1.0 in steps of 0.1 to 0.001. The last value is chosen to avoid technologies being scaled to their maximum size, despite not being in use and thus having no operating cost assigned.

The results of the Pareto analysis for the six scenarios can be seen in Figure 20, with the detailed cost distributions in terms of operating costs and investment costs shown in Figure 21. The lowest overall cost obtained is of 9.33M€/y and is obtained when using a battery and non-renewable technologies for an $\alpha^{inv} = 0.5$. It is composed of an operating cost of 5.46M€/y and an investment cost of 3.87M€/y. Slightly higher minimum total costs of 9.40M€/y are obtained in the scenario where no energy storage is allowed. The battery is observed to perform well in further decreasing operating costs at only a slight increase of total costs. For instance, reducing the operating costs by 47.7% to 2.86M€/y leads only to a 7.2% increase of the total costs to 10.00M€/y. When not allowing battery storage, even an operating cost of 3.79M€/y can only be achieved with a total cost of 16.42M€/y. In fact, this is higher than the required investment cost of 15.87M€/y for achieving zero operating cost with the battery. The latter displays that with 70.1% total cost increase compared to the optimal solution, the battery allows to completely avoid operating cost.

In the fully renewable scenarios, where natural gas is not allowed, the minimum total costs increase both with and without battery storage. In the scenario not allowing any energy storage, the minimum costs increase by 22.7% to 11.54M€/y. When allowing for battery storage, the minimum costs only increase by 16.2% to 10.84M€/y. The advantage of using the battery for minimising total costs is thus increased from a 0.8% to a 6.1% lower cost achievable when not allowing non-renewable technologies anymore. It can thus be concluded that while the battery has no significant advantage for conventional energy systems using fossil resources, in fully renewable energy systems relying partially on intermittent energy sources, the battery is a competitive technology for minimising the total costs of the system.

When allowing for the integration of hydrogen technologies, the hydrogen storage system is not employed in the optimisation minimising total costs with an $\alpha^{inv} = 0.5$. It is only employed for $\alpha^{inv} \leq 0.2$, which displays the important investment cost needed for levelling intermittent energy supply using a hydrogen storage system, especially for the electrolysers and fuel cells. Even when reducing investment costs of all hydrogen technologies by 50%, this type of energy storage is only employed for $\alpha^{inv} \leq 0.3$. In the most cost optimal solution where hydrogen storage is employed for the scenario without a cost reduction for hydrogen technologies ($\alpha^{inv} = 0.2$), the implementation of the hydrogen technologies requires total costs of 13.59M€/y, being 45.6% higher than the minimum total costs when using a battery. Even when reducing the investment costs by 50%, the minimum total costs of 10.78M€/y are 15.5% higher than when using a battery. Moreover, from Figure 20 it can clearly be seen that the hydrogen storage system does not allow to reduce operating costs as efficiently as the battery. Thus, it can be concluded that the high investment costs and the lower round-trip-efficiency of the hydrogen storage system make the battery the more competitive energy storage option. The latter is mostly used to level intermittency of energy production on a daily and not seasonal basis, as will be seen in section 5.1.3.

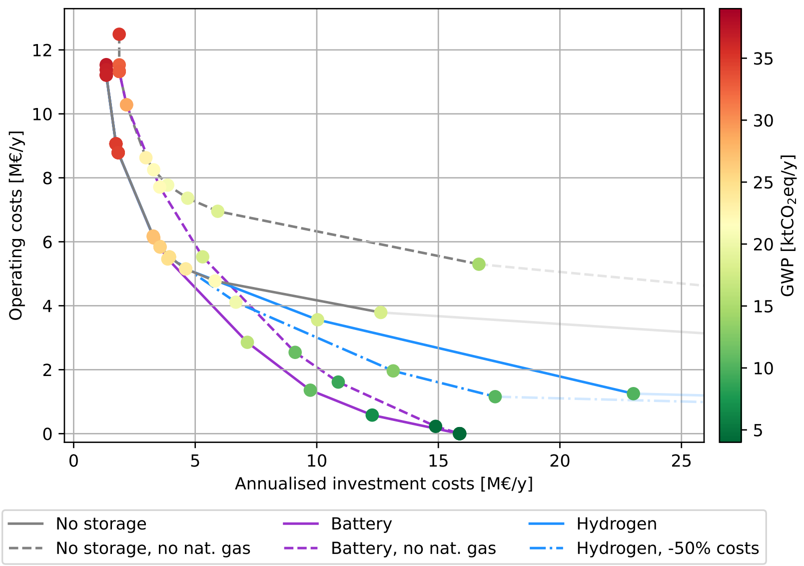


Figure 20: Pareto front for different scenarios analysed

In Figure 21, the investment and operating cost distributions per technology of all 66 generated solutions are displayed. It can be observed that when optimising only on investment costs, energy systems relying on natural gas boilers, chillers and electricity from the grid are the most common option, as visible for example in Subfigure 21(a). When prohibiting the use of natural gas, as done in Subfigure 21(b), the natural gas boiler is replaced with a heat pump to minimise investment costs.

When reducing overall costs, the best solutions obtained are employing a combination of a combined cycle running on natural gas, a CO_2 network, PV and electricity from the grid, as again visible for example in Subfigure 21(a). As discussed before, even lower total costs are observed when allowing the use of a battery, as visible in Subfigure 21(c). The combined cycle is replaced with a larger CO_2 network and an increased battery capacity when prohibiting the use of natural gas.

Finally, when optimising operating costs with $\alpha^{inv} = 0.001$, except when integrating batteries, solutions with unreasonably high investment costs are obtained (visible in Subfigures 21(a), 21(b), 21(e) and 21(f)). In those solutions, the optimisation is choosing to import a maximum amount of electricity when grid prices are negative and is then dissipating the electricity using additional units not necessary for fulfilling the demand. Despite constraining that the yearly sum of the costs for buying grid electricity cannot be negative, solutions with unreasonably high investment costs are still obtained. In consequence, it is decided to disregard those solutions in the future analysis, as they are neither competitive, nor sustainable or energy efficient.

5.1.2 Selected Solutions for Detailed Analysis

From the Pareto analysis depicted in section 5.1.1, the most common technology combinations are obtained. For each configuration characterised by the main technologies employed, the solutions with minimum total costs are selected, in order to observe the performance of all technologies employed. Furthermore, for the configurations including storage units, solutions with different storage sizes are chosen to observe the impact of a higher storage capacity. The solutions are analysed for different key performance indicators relating to investment and operating costs, as was done in the previous subsection.

Table 8 gives an overview of the selected solutions. It can be seen that all technologies are employed in at least one of the solutions as a main technology. Five technology configurations not using natural gas and seven technology combinations using natural gas are selected. Furthermore, six technology combinations employ no storage unit, four technology combinations employ a battery and two technology combinations the hydrogen tank. The most frequent solution for the scenario with no storage unit uses PV, a combined cycle and a CO_2 network. When employing the battery, the most frequent solutions are using, next to the battery, PV and a CO_2 network, with an additional combined cycle when allowing non-renewable technologies. One of the solutions employing the hydrogen tank furthermore make use of a mini wind turbine. An overview of the installed technology capacities can be found in Appendix C, which also allows the verification of these configurations, including the costs.

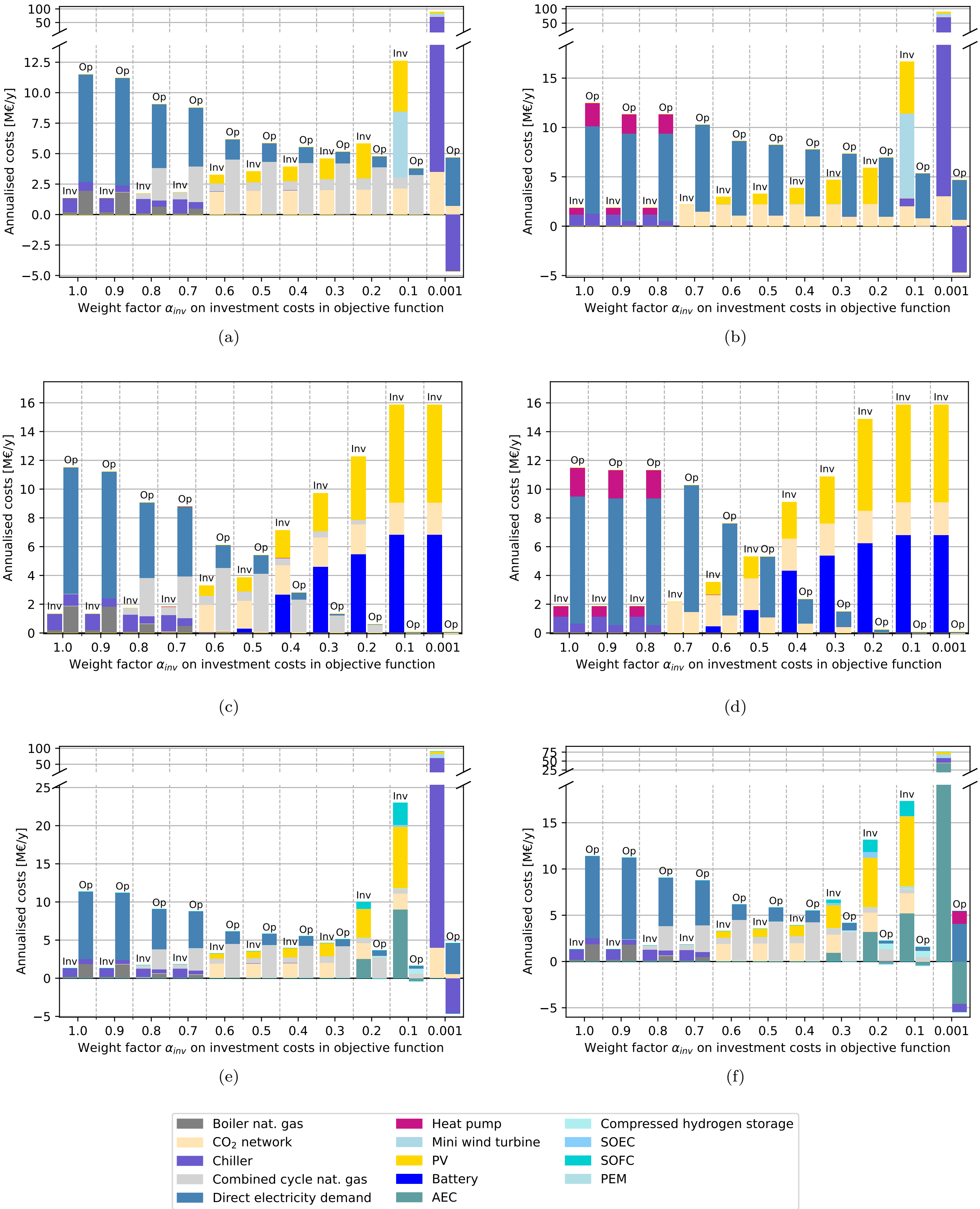


Figure 21: Cost distribution for the different points shown in the pareto front plot in Figure 20 for the scenarios with (a) no storage units, (b) no storage units and no natural gas, (c) only battery storage, (d) only battery storage and no natural gas, (e) only hydrogen storage and (f) only hydrogen storage with hydrogen units at 50% reduced costs

Table 8: Overview of selected solutions for further analysis from the Pareto front in Figure 20

Solution name	Number of occurrences	Optimisation		Main technologies									
		Scenario	α^{inv}	Battery (BAT)	Hydrogen storage (H_2S)	Grid electricity	PV (PV)	Mini wind turbine (WT)	Combined cycle (CC)	Boiler (BOI)	Heat Pump (HP)	CO_2 network (CO_2N)	Chiller (CHI)
BOI+CHI	8	No storage	0.9			X				X			X
CC+BOI+CHI	8	No storage	0.7			X			X	X			X
HP+CHI	6	No storage, no nat. gas	0.8			X					X		X
PV+CO_2N	4	No storage, no nat. gas	0.5			X	X					X	
PV+CC+CO_2N	13	No storage	0.5			X	X		X			X	
PV+WT+CO_2N	1	No storage, no nat. gas	0.1			X	X	X				X	
BAT+PV+CC+CO_2N	4	Batteries	0.5	X		X	X		X			X	
BAT+PV+CO_2N	9	Batteries, no nat. gas	0.5	X		X	X					X	
XBAT+PV+CC+CO_2N	(4)	Batteries	0.3	X		X	X		X			X	
XBAT+PV+CO_2N	(9)	Batteries, no nat. gas	0.2	X		X	X					X	
H_2S+PV+CC+CO_2N	4	Hydrogen storage	0.2		X	X	X		X			X	
XH_2S+PV+CC+CO_2N	(4)	Hydrogen storage	0.1		X	X	X		X			X	

From the overview of the technologies, it can already be concluded that the PV, the combined cycle and the CO_2 network are the most commonly employed technologies in the optimised energy systems. They are being used both in different scenarios as well as for different objective functions, which proves their competitiveness under varying circumstances. The robustness of the configurations will further be analysed in section 5.3, where the optimisation will be extended to different airport environments.

It is important to be aware of the limitations of this approach when analysing the results for the selected energy systems. With the Pareto analysis, a number of feasible configurations are created that perform variously well either in terms of operating, investment costs or a combination of both. When looking at different key performance indicators, it is important to note that the configurations have not been optimized for those. Although the configurations give a good overview of achievable values, the range of results does not allow final conclusions to be drawn about the maximum possible performance. A further analysis in future studies would be required that specifically optimises the performance of individual key performance indicators and creates configurations for them.

For the selected solutions, the key performance indicators are computed and displayed in Figure 22. These include the yearly total costs as already shown before, the GWP, the share of renewable energy used, the energy system self-sufficiency and the exergy efficiency of the energy system. The latter efficiency is calculated excluding the exergy efficiency of PV, to avoid penalising solutions with a high area of PV installed.

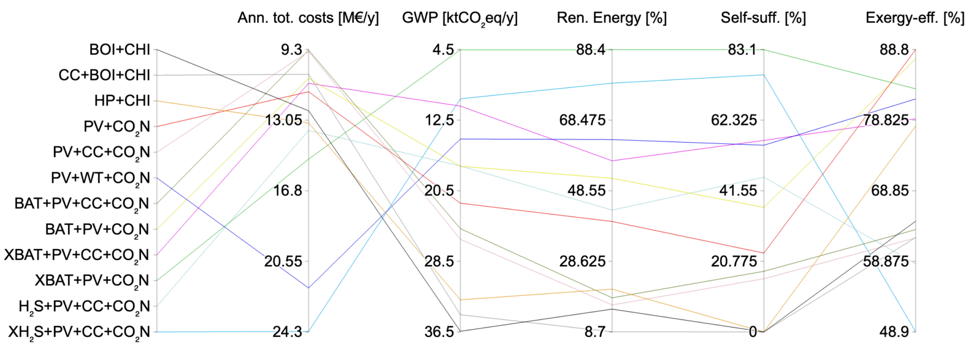


Figure 22: Key performance indicators of selected solutions from Pareto fronts from different scenarios, as described in Table 8

Different observations can be made. First, the solutions employing natural gas boilers (BOI+CHI and CC+BOI+CHI) are looked at. While having overall costs comparable to the remaining energy system configurations, they display the highest GWP of 36.4ktCO_2eq/y and 34.5ktCO_2eq/y, but the lowest share of renewable energy with not more than 15.1% and a self-sufficiency of 0%. When replacing the boiler with a heat pump, as is done in the configuration HP+CHI, very similar results are obtained with a slightly lower GWP (4.9% lower than for the solution with a combined cycle, a boiler and a chiller) and an improved exergy efficiency of 78.0%, being in the higher range of efficiencies from all configurations.

The GWP is significantly reduced when adding PV to the energy system, thus avoiding part of the emissions associated to the electricity from the grid. In combination with a CO_2 network and both without (PV+CO_2N) and with a combined cycle for local electricity generation from natural gas (PV+CC+CO_2N), a medium to low GWP (21.9 and 26.0ktCO_2eq/y), renewable energy share (39.9% and 16.3%) and self-sufficiency (23.2% and 15.7%) are obtained compared to the other solutions. Nevertheless, the solution including the combined cycle scores second best for the total costs (9.4M€/y), whereas the one only with PV and a CO_2 network scores highest for the exergy efficiency, with a value of 88.8%.

When adding a battery to those two configurations, as is done in BAT+PV+CC+CO_2N and BAT+PV+CO_2N similar exergy efficiencies and costs are obtained, with the former solution having the lowest total costs of 9.3M€/y. However, in the case with no combined cycle, the GWP is further reduced down to 17.7ktCO_2eq/y and the renewable energy and self-sufficiency shares are improved to 52.1% and 36.7% respectively.

While having only a slightly higher total cost of 11.1M€/y than the previous battery solutions, the configuration XBAT+PV+CC+CO_2N, employing a battery with a significantly higher capacity of 146.2MWh, has a reduced GWP of 10.9ktCO_2eq/y and a relatively high renewable energy share and self-sufficiency of 57.0% and 56.4% respectively. The solution without using a storage but adding mini wind turbines (PV+WT+CO_2N) allows to achieve a close GWP of 14.6ktCO_2eq/y, which is the best of all configurations without storage technologies. Furthermore, this solution allows to obtain a similar renewable energy share of 63.0% and self-sufficiency of 54.9%. However, the total costs when introducing mini wind turbines are 22.0M€/y and thus 98.2% higher than for the comparable battery configuration (XBAT+PV+CC+CO_2N).

The last battery configuration XBAT+PV+CO_2N with a 35.9% higher battery capacity of 198.7MWh strikes out for three of the key performance indicators. It has the lowest GWP (4.5ktCO_2eq/y), displays the highest share of 88.4% renewable energies and displays the second highest self-sufficiency of 83.1%. Meanwhile, it has an average exergy efficiency and only a 61.8% higher cost of 15.1M€/y than the configuration with the lowest total cost. Thus, this configuration shows that self-sufficiencies of above 80% are possible at acceptable costs, whereas self-sufficiencies of 90% or more require investment costs which are at least twice the minimum investment costs.

Finally, the configurations employing a hydrogen tank can be looked at. The least expensive hydrogen configuration (H_2S+PV+CC+CO_2N) with a hydrogen storage capacity of 104.7MWh displays similar results to the remaining solutions, due to the relatively small scale of the hydrogen system. However its exergy efficiency is only 58.5% and thus the second lowest of all configurations due to the low round trip efficiency of hydrogen storage. The lowest exergy efficiency of 48.9% is obtained for the second configuration including a hydrogen storage system (XH_2S+PV+CC+CO_2N). While furthermore displaying the highest total costs of 24.3M€/y, this configuration on the other hand has the second lowest GWP, renewable and self-sufficiency due to a hydrogen storage capacity of 276.9MWh.

Overall, it can be seen that including a natural gas boiler particularly decreases the performance of the energy system by provoking a low self-sufficiency and GWP. While having comparable emission values, when employed, the combined cycle from natural gas often complements PV in electricity generation and thus most configurations including it display better performances in terms of GWP, renewable energy share and self-sufficiency. Next, it can be concluded that the CO_2 network is a significant contributor to solutions scoring well in terms of GWP, renewable energy share and self-sufficiency, while having costs and efficiencies comparable to the remaining solutions, and is thus a very efficient and attractive solution for heating and cooling of the building. Furthermore, it can be observed that PV have a crucial importance for increasing the self-sufficiency and reducing the GWP by avoiding the emissions associated with the grid. Finally, the most important contribution towards a low GWP and high self-sufficiency is the introduction of storage units, which allow to store on-site generated green electricity and to use it during periods with no production but high demand. For the two types of storage units implemented, batteries show better performance than hydrogen storage in terms of costs and exergy efficiency.

Below, the composition of the scope-1 and -2 emissions contributing to the GWP can be seen in Figure 23. It can be observed that for most configurations, the largest contribution comes from the emissions associated to the grid electricity due to the large demand of electricity, representing approximately 2/3 of the overall energy demand. In fact, the share of the grid electricity in the overall emissions ranges from 25.2% for a configuration involving a battery to 77.4% for the solution with a natural gas boiler and 100% for the solutions with no natural gas consumption. The overall yearly emissions range from 36.4ktCO_2eq/y for the configuration using a boiler to 4.5ktCO_2eq/y for the solution only using the largest battery, a PV, a CO_2 network and a small amount of grid electricity. The combined cycle allows to reduce CO_2 emissions from the grid substantially by supplementing electricity supply in off-peak periods. Overall, it can be concluded that considerable CO_2 emission reductions can be obtained with an optimised energy system, but an important contribution also needs to be made by the grid electricity providers in transitioning to renewable electricity generation technologies and reducing emissions associated to the grid.

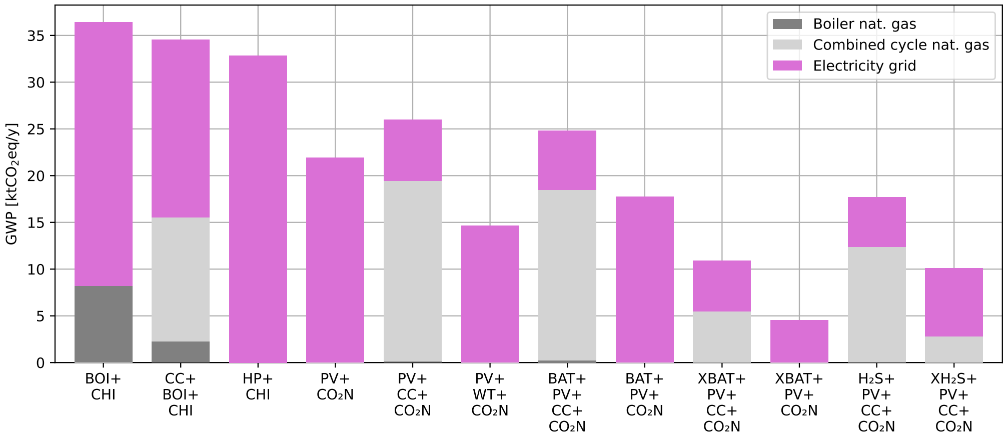


Figure 23: GWP distribution from yearly emissions of selected solutions from Pareto fronts from different scenarios, as described in Table 8

The yearly results obtained for the GWP can be compared to the greenhouse gas emissions of the Royal Schiphol Group for 2023, which provides combined scope-1 and -2 emissions of 75.7ktCO_2eq/y [16]. The emissions of the proposed energy system configurations are observed to be 2 to 17 times smaller, indicating the reduction potential through integrating renewable technologies and local electricity production. However, this comparison should be treated with caution, as the stated emissions may include additional emission sources and airport components that are not modelled in this optimisation framework. Furthermore, the emissions indicated by the Royal Schiphol group also include the emissions of Rotterdam The Hague airport and Eindhoven airport, which are, however, significantly smaller.

Moreover, the electricity mix of the airport over the full year for the different scenarios is shown in Figure 24. It allows to observe both differences in the electricity mix as well as for the overall amount of electricity consumed.

Different seasonal trends can be observed. For the PV, supply is highest during summer, when solar radiation also is strongest, as can be seen in Figure 13. On the other hand, the combined cycle as well as the electricity grid are compensating intermittency of PV electricity supply and are thus highest during winter, when being in use together, as can be seen for example in Subfigure 24(e). Moreover, they are also supplementary to each other with the combined cycle being used most when electricity from the grid is expensive. As can be seen in Subfigure 24(f), the supplementary behaviour of the combined cycle could be replaced by the mini wind turbine at an increased investment cost, as can be seen in Figure 22.

The battery can be observed to supply electricity more or less constantly over the full year, as can for example be seen in Subfigure 24(j). The nearly constant supply from the batteries shows that it is mostly used for daily and not for seasonal storage, as will be explained also in section 5.1.3. Furthermore, from Subfigure 24(i) it can be seen that the share in supply from the battery is lower in periods with higher electricity production from the combined cycle of natural gas, as the latter is used to compensate the smaller potential of renewable electricity production, which also causes a smaller energy storage potential in those periods. Similar observations can be made for the hydrogen storage system with the SOFC supplying electricity, which can for example be seen in Subfigure 24(k). However, the hydrogen storage system displays much smaller overall supply than the battery.

When looking at the overall supply of electricity, it can be seen that it is lowest for the solution employing boilers or combined cycles with 102GWh to 109GWh as they are not requiring any electricity for heating. Adding heating technologies based on electricity as well as energy storage technologies increases the overall electricity consumption of the energy system, leading to overall yearly consumptions of 111GWh to 125GWh. The highest yearly electricity consumptions of 132GWh to 192GWh are observed for the energy systems involving hydrogen storage due to its low round trip efficiency, as can be seen especially in Subfigure 24(l).

Finally, the overall yearly production of PV electricity can be looked at. It is observed to range from 24GWh for the configuration PV+CC+CO_2N in Subfigure 24(e) to 192GWh for XH_2S+PV+CC+CO_2N in Subfigure 24(l). In 2023, 2.3GWh of PV energy were produced at Amsterdam Schiphol [5]. The proposed configurations including PV energy would thus at least multiply this capacity by a factor of 10. They would require total PV surface areas of 0.13km^2 to 1.13km^2. It needs to be confirmed whether enough surface around the airport can be used for such a large-scale installation of PV, also taking into account the glare and radio effects of their deployment. However, it can be noted that studies for smaller airports have already identified potential of a similar magnitude [98]. Similarly, for the energy system configuration PV+WT+CO_2N as shown in Subfigure 24(f), it needs to be verified whether the installation of 2535 mini wind turbines is possible around the airport.

Figure 24: Weekly moving average of electricity supply distribution and electricity supply from storage technologies over the year for the scenarios described in Table 8

5.1.3 Option of Fully Independent Energy System

All of the solutions presented in the previous subsection include the electricity grid as a source of electricity. Even when minimising for zero operating costs, grid electricity at negative and minor positive prices is used. In this subsection, the option of a fully independent energy system without any connection to both the electricity and natural gas grid is analysed.

Whilst having a zero GWP, running fully on renewable energy and being self-sufficient, this energy system configuration displays total investment costs of 32.5M€/y, which are 248.3% higher than the lowest cost obtained from the configurations in section 5.1.1. It can be seen that obtaining a fully-self-sufficient energy system comes at a significant investment cost, whereas self-sufficiencies of around 80% can be obtained at reasonable costs of up to 15.5M€/y, as is shown in Figure 22.

As can be seen in Figure 25, the electricity mix of this configuration consists of electricity from batteries, PV and mini wind turbines. A surface area of 1.02km^2 of PV, 4033 mini wind turbines and a battery capacity of 296.3MWh is installed in this solution, where the PV, the mini wind turbines and the battery represent 22.2%, 42.2% and 28.7% of the overall costs respectively. This displays the significant investment and footprint required for mini wind turbines for only providing a small share of 18.5% of the yearly electricity supply. It can be observed that during summer, PV are the most important electricity source, whereas during winter, mini wind turbines have an equal or even higher share of the generated electricity. Moreover, the battery is 49.1% larger than the largest battery from the selected Pareto configurations. It is again used primarily as a daily storage unit with no significant seasonal variations.

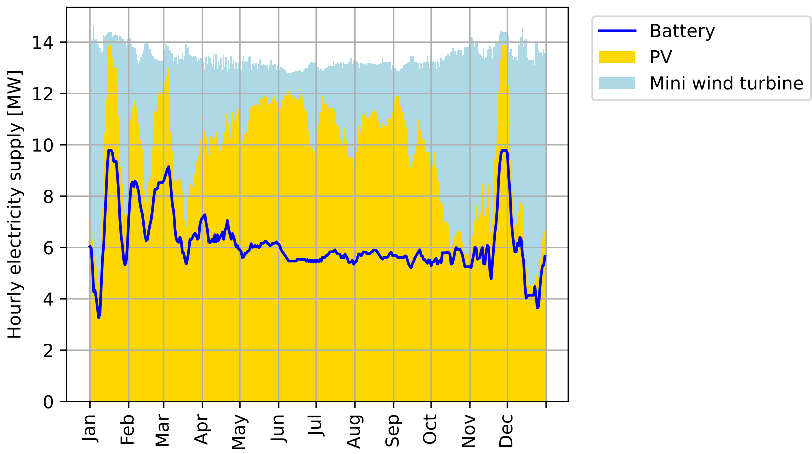


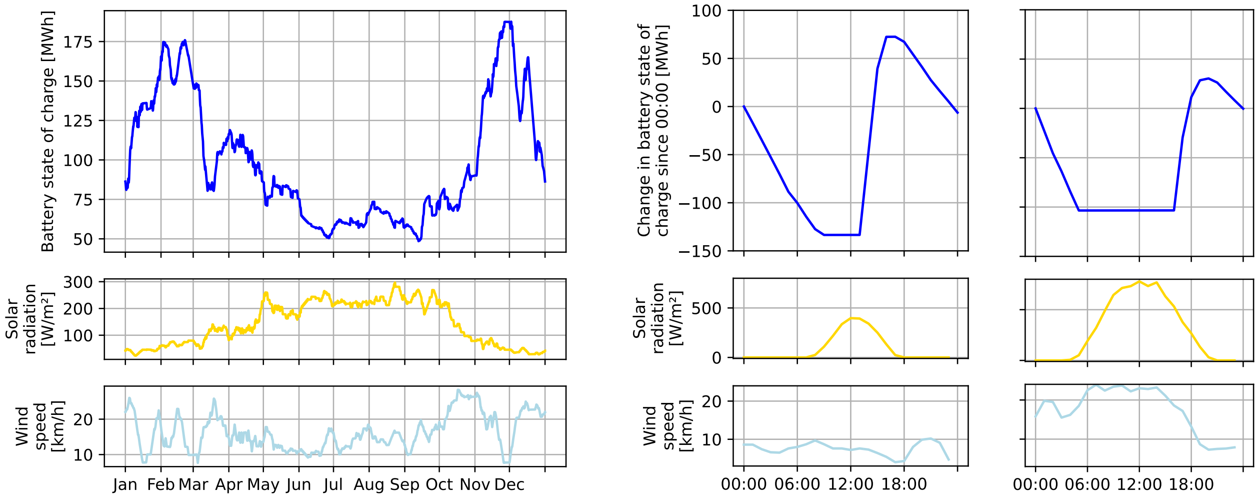
Figure 25: Weekly moving average of electricity supply distribution and electricity supply from storage technologies for scenario with battery and no connection to electricity or natural gas grid

It must be noted that the potential of PV power to be generated in summer is higher than the actual electricity generated. Throughout the year, only 37.6% of the potential PV electricity is used at the airport itself, while the additional potential electricity is not generated due to curtailment of the PV. It may be promising for future research to analyse whether this additional electricity could be fed into the national grid at profitable prices for the airport. When selling the potential excess electricity at varying grid prices, a maximal revenue of 7.3M€/y would be possible, which would reduce the yearly total costs of this configuration by 22.5%.

Next to the electricity mix over the full year, it is interesting to look into the battery's performance specifically, which is used more than in the previous scenarios. Figure 26 shows the battery use profile together with the input data for the solar radiation and the wind speed, both for the full year as well as for two typical days, a winter and a summer day, with different solar radiation and wind speed characteristics.

Computing the overall amplitude for seasonal and daily variation, it is possible to see that the daily variation of the battery state of charge is approximately as large as the seasonal variation for the summer day and nearly twice as large for the winter day. Furthermore, when looking at the change in state of charge at the end of one day, only a minor difference can be observed compared to the beginning of the day. This indicates that the battery is used more as a daily than as a seasonal storage unit, as no significant state of charge is accumulated over the year. The daily storage behaviour allows the battery to store electricity for the night when no solar radiation is available.

When comparing the state of charge to the solar radiation and wind speed profile, as expected, it can be seen that the battery is charging when there is a lot of solar radiation and wind available and that it supplies electricity during off-peak periods. This can be seen particularly well for the daily profile of the winter day, where the battery charges during the full time period in which solar radiation is available, in order to store



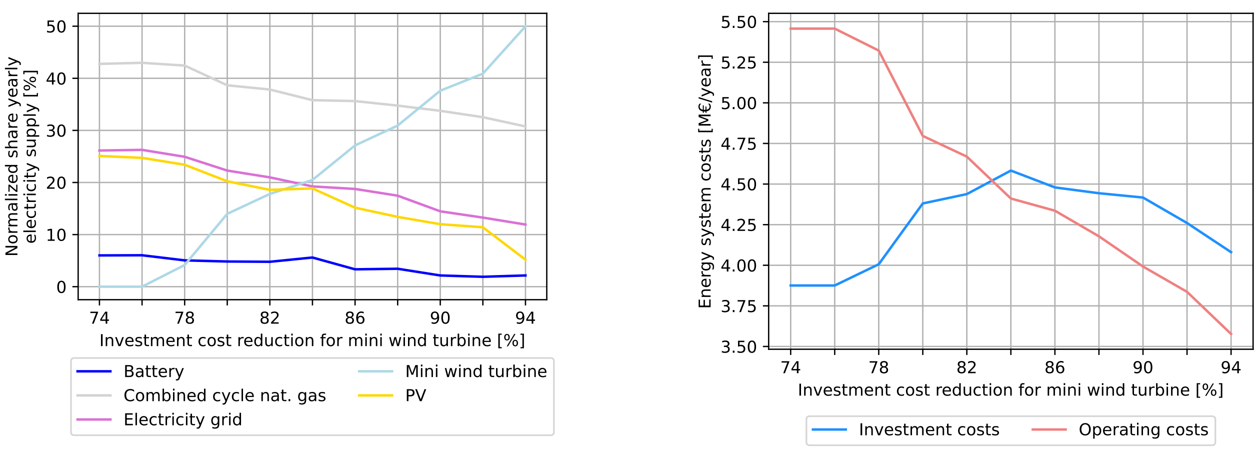
(a) (b) (c)

Figure 26: Battery state of charge (a) for the full year (weekly moving average) and (b) for a typical winter day (typical day 6) and a typical summer day (typical day 10) combined with solar radiation and wind speed

enough energy for the night. In the case of the summer day, the battery only charges at the end of the day when solar radiation and wind speed reduce to insufficient levels for providing the required energy for the airport. From Figure 25, it can furthermore be observed that daily storage is particularly important during winter days with less wind energy generated. As the battery is mainly used as a daily storage unit, the seasonal profile in Figure 26 does not display those clear parallels. Nevertheless, a lower average state of charge can be observed during summer, which confirms that the use of the battery is most important during extreme winter days.

5.1.4 Sensitivity Analysis

From the Pareto analysis, it can be observed that all units occur in at least one of the selected scenarios but that some technologies only occur at a low weight on the investment cost, for example, the mini wind turbine, which only occurs for $\alpha^{inv} = 0.1$. This is due to the high investment cost of the mini wind turbine compared to the other local electricity generation technologies. In fact, with the implemented costs and the weather characteristics of Amsterdam, the investment costs required for installing a PV with an output of 1MWh per year are 332€ whereas a mini wind turbine with an equivalent yearly electricity output requires an investment of $2,483$€. Thus, mini wind turbines would require a significant decrease in investment costs to be competitive local electricity generation technologies. Figure 27 displays how the usage of the mini wind turbine changes at decreased investment costs when minimising the total costs of the energy system.

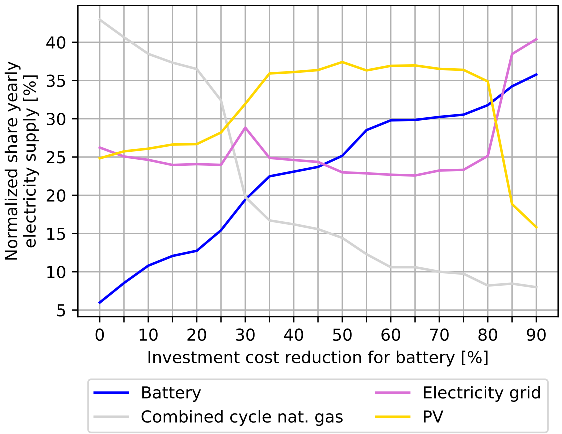


(a) (b)

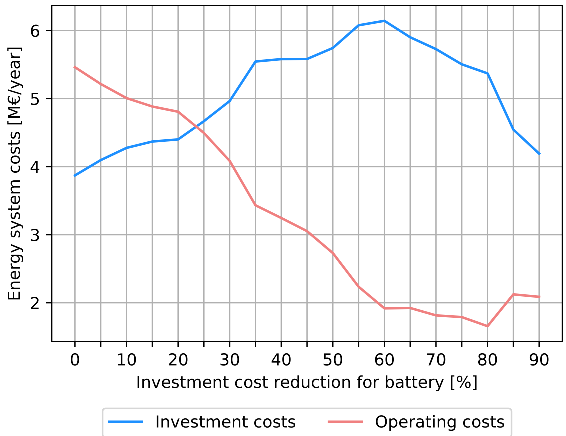
Figure 27: Resulting electricity supply distribution (a) and overall yearly energy system costs (b) for sensitivity analysis on investment costs of mini wind turbine

From the sensitivity analysis, it can be observed that, only with a decrease of 76% in investment costs, the mini wind turbine will be used as an additional local electricity generation technology. First, it only complements the PV in producing local electricity. When installing additional mini wind turbines, the size of the battery is reduced as less electricity needs to be stored from day- to nighttime. At a cost reduction of 83%, the share of mini wind turbines in the generation of electricity is surpassing the share of solar cells, which is in line with the investment cost ratio between mini wind turbines and PV, the latter having an 87% lower investment cost per MWh produced. Moreover, it can be observed that a decreased cost for the mini wind turbines allows for a decrease in dependency on natural gas combined cycles and grid electricity in the airport's electricity mix and thus allows for a reduction in operating costs and overall costs at an increased investment cost.

Next, the sensitivity of the usage of storage technologies at reduced investment costs can be looked at. First, the effect of reducing the investment cost of batteries in optimisations minimising the total costs of the energy system is analysed. The resulting electricity mix and cost distribution are shown in Figure 28.



(a)



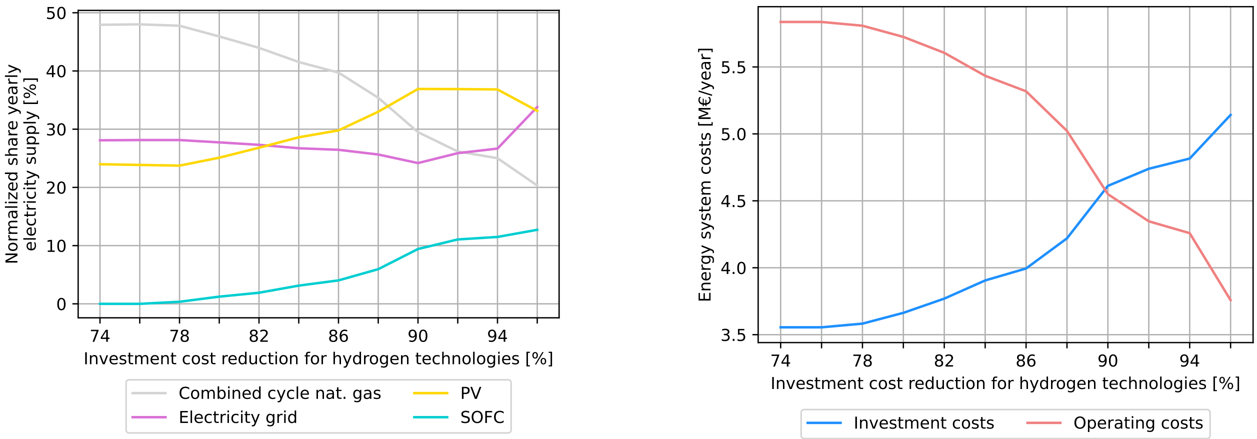
(b)

Figure 28: Resulting electricity supply distribution (a) and overall yearly energy system costs (b) for sensitivity analysis on investment costs of battery

When optimising the energy system for minimum costs, already at the pre-defined costs, the battery ensures approximately 6% of the yearly electricity supply. It can be seen that this share gradually increases when the investment costs of the battery decrease. Meanwhile, the share of the combined cycle from natural gas decreases, while the share of PV electricity increases, indicating that producing and storing solar power becomes more profitable than producing electricity from fossil resources. At a 60% reduction of the investment cost of the battery, the share of the battery and PV increased from 6% and 25% to 30% and 37%, respectively, in the yearly electricity supply, whereas the importance of the combined cycle decreased from 43% to 11%. This shows that a decreased battery investment cost allows the decarbonization of the airport's energy system and the reduction of operating costs at a lower increase in investment costs. At investment cost reductions higher than 80%, the grid electricity increases its share in the electricity supply while the importance of the PV decreases, indicating that the battery is now increasingly used to store electricity bought at low prices for usage in periods with high electricity prices while producing less electricity on site.

Unlike the battery, hydrogen storage is not observed to be useful when minimising the total costs of the energy system. Figure 29 displays the sensitivity of the hydrogen storage system use when only including the hydrogen system as storage technology and decreasing the costs of all hydrogen technologies, being the electrolysers, the storage tank and the fuel cell.

It can be observed that the hydrogen storage system starts being used at an investment cost reduction of 76%. Similar to the battery, together with the PV, it allows for the reduction of the share of the combined cycle in the electricity mix, as well as the reduction of the share of grid electricity. After decreasing the hydrogen technology investment costs by 94%, the hydrogen fuel cell and PV increase their share in the electricity mix from 0% and 24% to 12% and 37%, respectively, whereas the share of the combined cycle and grid electricity decreased from 48% and 28% to 25% and 27%, respectively. Similarly to the battery, at higher cost reductions, the importance of the grid electricity in the electricity mix rises, whereas the importance of the PV and the combined cycle (further) decreases. Overall, the hydrogen storage system also decarbonises the electricity supply system and reduces operating and overall costs, but only to a smaller extent than the battery and only at significant cost



(a) (b)

Figure 29: Resulting electricity supply distribution (a) and overall yearly energy system costs (b) for sensitivity analysis on investment costs of hydrogen technologies

reductions of at least 76% for the hydrogen technologies. These reduction values must however be interpreted with caution and only in combination with the assumed costs for the technologies, as, like all other results on costs and generally all results of the optimisation, differences in the assumptions could considerably influence the conclusions.

5.2 Production of Synthetic Fuels at the Airport

As is shown in Figure 7 (on page 12), next to the energy technologies fulfilling heating, cooling and electricity demands, a pathway for the production of synthetic fuels is implemented in the superstructure. Optimisations are performed to analyse if integrating those technologies at the airport and selling the synthetic fuels would be economically beneficial for the airport. Based on the overall kerosene demand at Amsterdam Schiphol in 2017 of 3.6Mt [146] as well as the annual aircraft movements of 514,625 in 2017 [147] and 464,727 in 2023 [148], a kerosene demand of 3.25Mt is computed for 2023.

In the first analysis, it is assumed that the production of synthetic fuels at Amsterdam Schiphol would fulfil 1% of the annual kerosene demand with a constant production rate over the year of 3.71t/h. As the models [117] and associated cost functions [119] are defined for an order of magnitude of 1t/h, this production rate is in a valid range of magnitude. It must be noted that the models employed produce a fuel mix with only 1% of kerosene, as is shown in Table 3 (on page 18). For future research, it would be relevant to include synthetic fuel separation optimised for producing a maximal output share of kerosene. For this study, it is assumed that the fuel mix can be sold at the prices without taxes of the individual fuels, which are displayed in Table 3.

First, the pathway of producing synthetic fuels from biogasification is analysed. The profitability of producing synthetic fuels at airports depends on the investment costs of the technologies as well as the feedstock and output product prices. As both the price for the biomass and the price for synthetic fuels are uncertain, the total energy system costs are computed for a range of values. The biomass price varied from 5€/t to 85€/t, as this price range represented most of the current biomass supply in the Netherlands [97]. For the synthetic fuel price obtained as a profit, a pricing factor is applied, indicating if 100%, 80% or 60% of the profit achievable at current fuel prices goes as revenue to the airport. Figure 30 displays the cost difference of the energy system for the different combinations of those two variables. The cost difference is defined as the difference in total costs, including investment costs, operating costs, and revenues from selling the synthetic fuels, with respect to the previously determined cost-optimal energy system, which has a cost of 9.43M€. It thus indicates the extent to which the production of synthetic fuels would favour or burden the airport.

From Figure 30 it can be observed that, at the assumed costs, the production of synthetic fuels would be beneficial to the airport in most scenarios. In fact, only when assuming that only 60% of the fuel prices would arrive as profit for the airport and at conservative biomass prices of 65€/t or higher, the airport would need to invest up to 5.0M€/y more than it would earn as revenue. When assuming the lowest biomass price of 5€/t, the airport would have a yearly revenue of 8.3M€/y. This possible revenue could even increase to 22.0M€/y if it is assumed that the airport would receive the full equivalent fuel price as a profit. The latter is composed of revenue of 34.5M€/y while having additional investment costs of 10.0M€/y and an additional operating cost of 2.5M€/y.

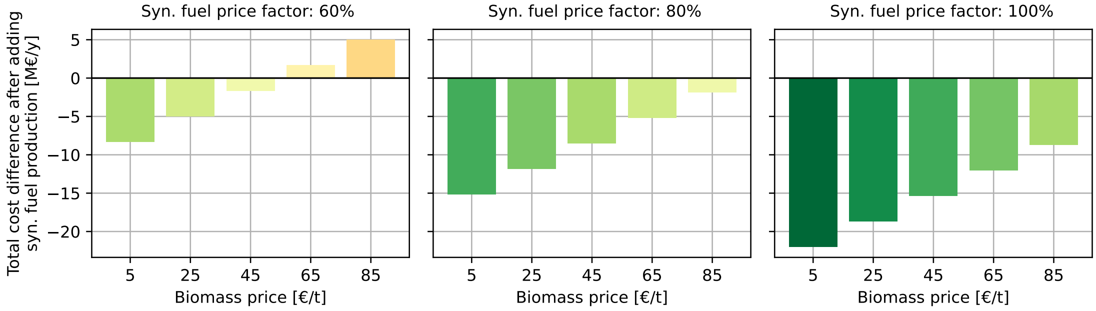


Figure 30: Difference in total energy system costs (for different biomass prices and synthetic fuel price factors) after addition of biogasification pathway compared to system with optimal cost without synthetic fuel production (9.5M€/y)

The second option implemented for the production of synthetic fuels is co-electrolysis from captured CO_2, for example from emissions of nearby industries, as was described previously in Figure 7. As the CO_2 is assumed to have a zero cost, the only variable considered for the co-electrolysis pathway is the synthetic fuel pricing factor. The resulting cost difference with respect to the cost-optimal energy system without the production of synthetic fuels can be seen in Figure 31.

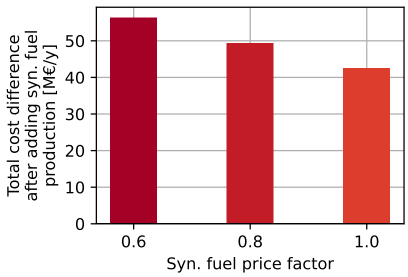


Figure 31: Difference in total energy system costs (for different synthetic fuel price factors) after addition of co-electrolysis pathway compared to system with optimal cost without synthetic fuel production (9.43M€/y)

It can be observed that the co-electrolysis pathway is significantly more expensive than the biogasification pathway. Instead of creating a profit for the airport, it increases its overall energy system costs by a factor higher than 5. When assuming that the full fuel price is received as a profit by the airport, an additional yearly cost of 42.6M€/y is required. When observing the cost distribution for this configuration, it can be seen that the energy resources in terms of grid electricity and natural gas, mostly required in the production of the synthetic fuels, have a yearly cost of 36.4M€/y, while only a profit of 34.3M€/y is generated per year from selling the fuels. Moreover, the required technologies in the co-electrolysis pathway have an annualised investment cost of 32.3M€/y, which does not yet include the additional costs from the supplementary capacities of combined cycles and PV.

Overall, the biogasification pathway displays promising results for producing synthetic fuels and, thus also, sustainable aviation fuel at the airport, whereas co-electrolysis does not seem to be a competitive option at the current technology development and costs. Due to the increasing importance of reducing emissions in aviation and, in consequence, the demand for sustainable aviation fuels, and with the current production capacities being not sufficient [149], it can be interesting for an airport to further investigate this option. For example, it could be analysed whether the production of sustainable aviation fuel from municipal waste could be profitable, as is proposed by Seiple at al. [150], especially considering the location of Amsterdam Schiphol within the densely populated Randstad region.

The two implemented pathways are to be built on for future analysis of the production of sustainable aviation fuels at the airport. First, the cost of the required additional infrastructure at the airport can be added to the cost of the technology, allowing to draw more precise conclusions on the profitability of the biogasification option. Further analysis could also include the investigation of different specific feedstocks available to the airport and their performance in producing sustainable aviation fuels. Furthermore, varying output rates, for example depending on the current electricity price, could be looked into, thus profiting from time periods of surplus electricity, as is proposed by Chen et al. [151]. Finally, the production at the airport site should be compared to different production locations, possibly closer to the feedstock, to investigate whether there is a benefit to produce the fuels at the airport.

5.3 Energy System Optimisation of Other European Airports

In the previous subsections, the energy system optimisation framework was applied to the case study of Amsterdam Schiphol airport. In this subsection, the analysis is extended to the five other European hub airports as presented in section 4.3. For all of the airports, the optimal configuration in terms of total costs is computed, both with all technologies in section 5.3.1 as well as with only technologies running on renewable resources in section 5.3.2. An overview of the technology capacities obtained in the optimised solutions for the different airports is included in Appendix C, which allows to verify the costs and the scale of the installed capacities.

5.3.1 Total Costs Optimised Solutions

As can be seen in section 4.3 (on page 25), the different European airports have different energy demands due to the airport building characteristics, the number of flights and passengers as well as the climate zone they are located in. Furthermore, the latter entails that they also have different potentials in terms of solar and wind power they can generate at their location. In consequence, it can be interesting to observe whether those different environments provoke different optimal energy system configurations when optimising for total costs. Thus, for all of the airports the energy system is optimised for minimal total costs and the resulting configurations are shown in Figure 32. For the optimisations, batteries are allowed as storage units, as these are observed to perform better in terms of cost from the analysis for Amsterdam Schiphol airport.

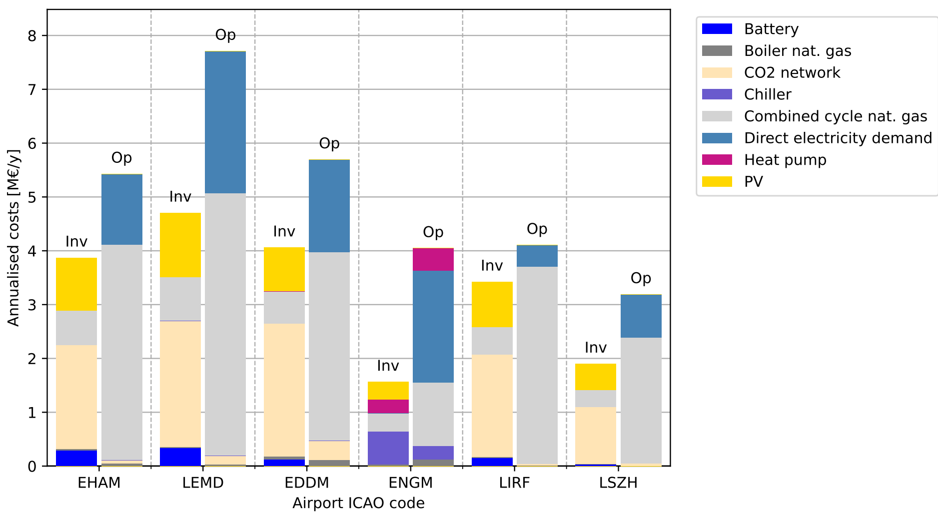


Figure 32: Comparison of energy system solutions for case-study European hub airports optimised for minimal total costs with batteries as available energy storage option

From the results, a most frequent configuration can be observed. For all airports except Oslo, the resulting energy system is composed of a combined cycle of natural gas, a relatively small boiler, a CO_2 network, PV, a small battery and electricity from the grid, with different relative sizes of these components depending on for example the solar radiation and the price of grid electricity. Oslo is the only airport with a different configuration for its energy system, not using a CO_2 network but a boiler, a combined cycle of natural gas, heat pumps and chillers for heating and cooling. This is due to the long airport buildings with respect to the overall surface area, making the required piping of the CO_2 network significantly more expensive.

From the key performance indicators, as displayed in Figure 33, it can be observed that Munich ranks lowest for the total costs and GWP per passenger with 0.23€/pax and 0.64kgCO_2eq/pax due to the large surface area per passenger, which needs to be supplied with energy. Zurich, for example, has a 38.9% lower surface area per passenger to supply with energy. Looking at the share of renewable energy, it can be seen that Oslo scores highest with 51.9% due to the large share of renewable energy in the Norwegian electricity grid. It is followed by the airport of Madrid with only 25.3%, which can slightly benefit of its large solar power potential due to the Mediterranean climate zone it is located in. Regarding self-sufficiency, Rome and Madrid perform best with 22.9% and 24.2% respectively, being the two cities with the highest solar power potential. On the other hand, Oslo has the lowest self-sufficiency of only 10.5% due to its low solar power potential. For the exergy efficiency of the airport, the airports are observed to perform similarly well. The airports with a high share of grid electricity perform best with exergy efficiencies of up to 63.4% in the case of Amsterdam.

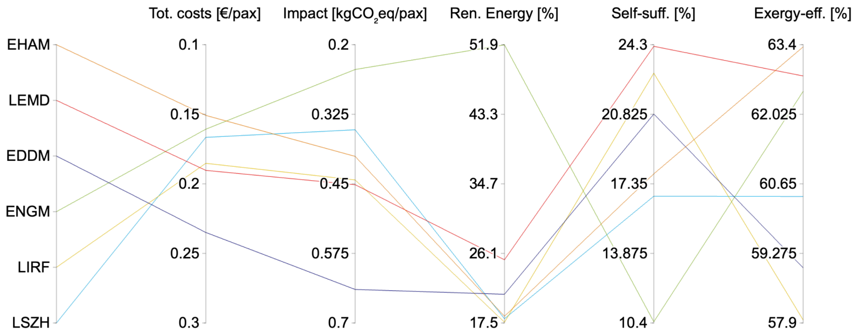


Figure 33: Comparison of key performance indicators for energy systems of case-study European hub airports optimised for minimal total costs with batteries as available energy storage option

5.3.2 Total Costs Optimised Solutions with only Renewable Technologies

In contrast to the previous results, for the optimisations performed in this subsection, the use of natural gas boilers and combined cycles is prohibited. The energy system is again optimised for minimal total costs. The different configurations obtained can be seen in Figure 34.

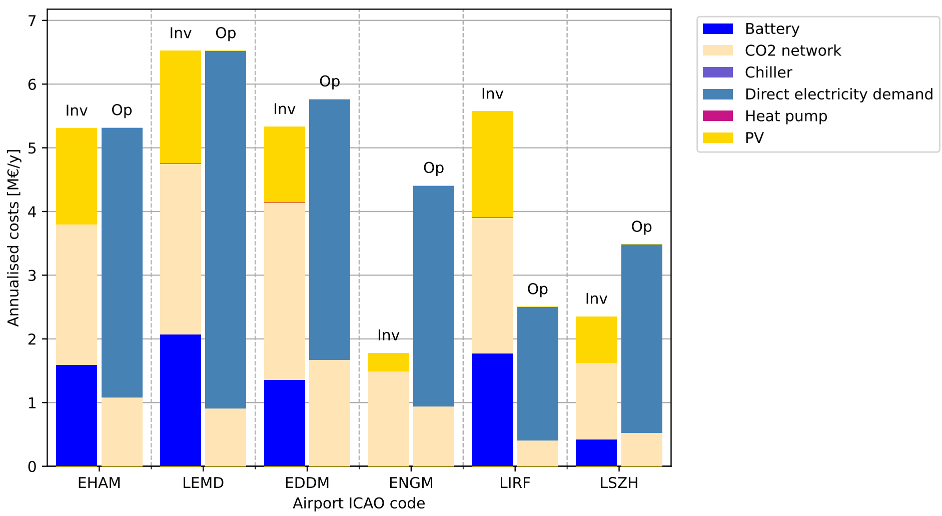


Figure 34: Comparison of energy system solutions for case-study European hub airports optimised for minimal total costs with batteries as available energy storage option and no natural gas

The configurations for the different airports with only renewable technologies look very similar. For all airports except Oslo, a combination of the CO_2 network, the battery, PV and electricity from the grid is employed. Again, Oslo has a configuration different from the other airports by not using a battery. This is most probably due to the small amount of PV installed at the airport, as Oslo has only a low solar power potential, and consequently the small amount of intermittent electricity generated which can be saved from day to night. Between the other airports, the distribution of technologies looks similar.

The key performance indicators are shown in Figure 35. From the results, the lowest yearly GWP is observed for Oslo and Zurich with 0.06kgCO$_2$eq/pax and 0.01kgCO$_2$eq/pax respectively due to the large share of renewable electricity in the electricity mix of the countries. Overall, the GWP decreases due to the avoided emissions from the combined cycle. The renewable energy share is again very high for Oslo with 95.5%. Despite having a very low GWP, Zurich scores with 70.1% significantly lower in terms of renewable energy share, as the electricity mix of Switzerland includes a large share of nuclear power, which is not renewable. In terms of self-sufficiency, the airports located in the Mediterranean climate zone with high solar power potential score higher with a self-sufficiency of 61.0% for Rome, whereas Oslo, located in the Boreal climate zone, heavily depends on the electricity grid and only has a self-sufficiency of 12.1%. The same effect can be observed for the installed PV capacities: While in Madrid and Rome 0.25km^2 and 0.23km^2 are employed respectively, the configuration of Oslo only uses 0.04km^2 of PV. This also affects the installed battery capacity, which is largest for Madrid with 65.6 MWh, while in Oslo no battery is employed.

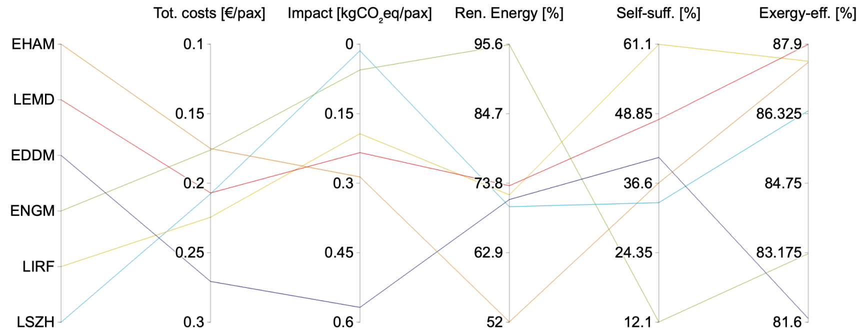


Figure 35: Comparison of key performance indicators for energy systems of case-study European hub airports optimised for minimal total costs with batteries as available energy storage option and no natural gas

Overall, two main configurations occur in the optimisations for the different airports. These are the combination of a CO_2 network, PV and a battery when only optimising with renewable technologies as well as an additional combined cycle from natural gas when allowing all technologies. Comparing these configurations to the different solutions in section 5.1.1, it can be seen that they coincide with the most frequent configurations in the Pareto fronts when optimising with and without batteries. Thus, it can be concluded that those energy system configurations are not only robust to different objectives while optimising, but also to different airport environments. Furthermore, in the Pareto analysis, it is seen that they do not only perform well in terms of costs, but also for their GWP and self-sufficiency, thus displaying an overall good performance for optimising the energy system of an airport.

Several points should be noted after interpreting the results for the different airports. First, for the five new airports, the specific energy demands are not validated by airport data, unlike for Amsterdam Schiphol. Only the overall order of magnitude is validated based on a set of 20 European airports. In addition, the building material and insulation might be different for all airports, which has a significant impact on the energy demand and is not yet taken into account by the energy demand model. Furthermore, the currently implemented configurations of the energy systems differ depending on the location, so that different pathways and transformation costs are needed for converting the respective airports' energy systems. Nevertheless, the model gives a good overview of feasible configurations depending on the location and airport configuration and provides a basis for future studies.

6 Conclusions

Airports are a significant source of emissions and energy consumption, with the yearly energy consumption of Amsterdam Schiphol being equivalent to the annual electricity consumption of 100,000 Dutch households. Consequently, optimising the energy systems of airports can contribute to reducing the aviation's environmental impact. The goal of this study was to develop an energy system model to analyse to what extent European airports, such as Amsterdam Schiphol airport, could benefit from the concept of renewable energy hubs in reducing their sustainability impact and increasing their energy supply self-sufficiency while fulfilling the varying energy demand profile from airport operations and infrastructure. It was found that a fully renewable energy system is possible at a limited total cost increase of approximately 20%. Self-sufficiencies of around 80% were observed to be viable in those energy system configurations combining photovoltaic cells (PV), a CO_2 network, batteries and electricity from the grid, which display robust results for varying airport environments.

The airport energy demand was estimated for the terminal and pier buildings and the airfield handling equipment. Combined, those two account for 61% of the energy consumption at Amsterdam Schiphol. Other important consumers are, for example, office buildings, hotels or hangars. The buildings' energy demand was split into heating, cooling, and ventilation; these were computed based on an estimate for the building envelope, hot water and remaining electricity demand. The energy consumption of the ground support equipment was determined based on reference data from actual ground support equipment manufacturers. The input parameters were defined as the number of flights and passengers, the building surface area and wall length, and weather data to make the model applicable to any airport. The demand was determined for an hourly profile, and the yearly energy demand was validated with actual airport energy demand data from Amsterdam Schiphol. The energy demand model allowed to obtain comparable results also for other European airports.

In the second step, an optimisation superstructure was constructed using the OSMOSE energy system optimisation framework developed at the Industrial Process and Energy Systems Engineering (IPESE) group of EPFL. The energy system can be optimised for the operating costs, investment costs and global warming potential (GWP) while respecting unit sizes, ensuring resource balance and obtaining a minimum energy requirement from the heat cascade. The energy demand data was clustered in typical days to reduce the computational load for mixed integer linear programming problems. The superstructure of possible energy technologies included multiple heating, cooling and electricity generation technologies, a battery and a hydrogen system for electricity storage as well as two pathways for producing synthetic fuels at the airport.

The optimisation framework was demonstrated by constructing different possible energy system configurations using a Pareto analysis for operating and investment costs. It was observed that the lowest overall costs of 9.3M€/y, consisting of operating and annualised investment costs of 3.9M€/y and 5.5M€/y respectively, were obtained in a configuration employing a CO_2 network, PV, a combined cycle from natural gas and grid electricity as well as a battery for electricity storage. With this configuration, a scope-1 and -2 GWP of 24.8ktCO_2/y, a renewable electricity share of 18.3% and a self-sufficiency of 17.8% were obtained. The latter can be significantly improved when energy storage technologies are used and when the combined cycle for heat and electricity production is avoided. When comparing the results from the optimisations for different airports, it was observed that most airports would employ energy system configurations similar to the ones proposed for Amsterdam Schiphol, showing the robustness of this combination of energy technologies.

A fully renewable energy system for the airport is possible at an overall cost increase of approximately 20%. However, the electricity grid still produces an essential amount of emissions, which must be decarbonized to avoid all scope-2 emissions. Results from different airports proved that an energy system consisting of a CO_2 network, PV, a battery and electricity from the grid is competitive to non-renewable energy systems in different environments. However, making the airport fully self-sufficient and independent of the grid is not competitive due to 248.3% higher total costs for this configuration. Self-sufficiencies of approximately 80% are achievable for the fully renewable energy system at total cost increases of only 60%.

Compared to the hydrogen system, battery storage is the most promising energy storage technology due to its higher round-trip efficiency and lower overall cost. The battery storage system is already used slightly for minimal-cost solutions and its usage increases in the case of possible future investment cost reductions. The hydrogen storage system would only be employed in minimal-cost configurations if its investment costs are reduced by 76%. A similar observation can be made for the mini wind turbines, which would only be employed as a local electricity production technology at investment cost reductions of approximately 76%, whereas the PV are already competitive at the current costs.

Finally, the models for producing synthetic fuels at the airport showed that those could be a possible future source of revenue for an airport. While the co-electrolysis pathway currently has too high investment and operating costs, the biogasification pathway from biomass would allow the production of synthetic fuels with profit, from synthetic fuels sales. At a biomass price of 5€/t and while considering the maximal assumed revenue achievable from selling the synthetic fuels, more than 20M€/y could be obtained per year from selling 1% of the sustainable aviation fuel demand at Amsterdam Schiphol, more than twice as high as the minimal overall annual energy system costs. While those results look promising, further analyses of the possible installation of those technologies at the airport is needed to validate those conclusions.

7 Recommendations

Overall, this study displays the potential of this energy system optimisation framework. The framework allows to analyse and compare possible airport energy system configurations in varying environments. Due to the broad applicability of the model and the wide set of possible technologies, however, several limitations exist and need to be kept in mind when interpreting its results. First, the heating, ventilation and cooling demand is estimated based on a simplified building model and does, for example, not take into account specific building material or insulation. Furthermore, the demand of other airports than Amsterdam Schiphol is not validated with specific heating, cooling and electricity demands of these airports but only its magnitude is confirmed by comparison with other European airports. For the optimisation results, it must be noted that the energy system is not optimised for all key performance indicators, but a set of feasible configurations is analysed and their key performance indicators are displayed. Next, the optimisation results depend on assumptions for technology characteristics and costs, which might have a significant influence on the results, as can be seen in the sensitivity analysis. Moreover, the pathway for transitioning from the current towards more renewable and self-sufficient energy systems at different airports needs to be developed. Future work can address these gaps and continue to build on this model.

First, the method for estimating the energy demand could be extended to the remaining parts of the airport outside of the terminal and pier buildings and the ground support equipment. It could additionally include multiple actors present in the airport environment, such as hotels, office buildings, etc. Demand clusters could be identified around the airport site, where an integration of the energy systems could be beneficial due to the proximity of complementing demands. Next to optimising the energy system for a pre-defined demand, possible demand reduction pathways could also be investigated. Furthermore, closer cooperation with airports would allow to improve and validate the hourly profiles generated and to obtain more detailed data for the building envelope.

Cooperation with airports would, furthermore, also allow to obtain more specific information on current energy systems and the characteristics of the technologies currently employed, which would allow the design of specific pathways for renewing and improving airport energy systems for the future. More technologies could be added to the superstructure, such as thermal storage, already employed at multiple Amsterdam Schiphol piers [152]. Exploring more long-term storage units, such as methane storage using power-to-methane processes [153] for reducing the dependency on the grid, could be interesting, as in this study especially daily storage units displayed good performances. Possible future technologies could be investigated and added to the superstructure, such as nuclear micro-reactors, which are suggested for the airport environment and are beneficial, especially in remote locations [154]. Promising technologies, such as the CO_2 network, could be further analysed for their use in the airport environment. Assuming future investment cost reductions for the hydrogen technologies, a combined battery and hydrogen storage system could also be investigated. Moreover, selling electricity from the airport to the grid could be considered, as well as investing in energy production and storage technologies in the airport region. The latter depends on the airport's location and could, for example, be near wind farms or hydropower plants.

Next, the potential of ground support equipment for an optimized energy system can be considered more closely. On the one hand, the effects of optimized ground support equipment operations, for example in the form of improved charging schedules, on charging demand and its distribution throughout the day can be considered. On the other hand, it can also be analysed to what extent using ground support equipment as a vehicle-to-grid technology, as is proposed in [50], would lead to a better performance of the overall energy system, for example by replacing battery capacities used for daily energy storage.

Finally, future analysis based on the model constructed could continue investigating in depth the option of producing synthetic fuels at the airport site. Additional resources, such as municipal waste from nearby cities [150] or CO_2 captured in the airport's ventilation system, could be analysed. The technology models implemented can be further adapted to the airport environment, and additional infrastructure costs and operational requirements can be considered. Finally, the fuel separation unit needs to be investigated in more detail and optimised for a maximal production of sustainable aviation fuels which can be sold at the airport.

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Appendices

A Verification of the Optimisation Framework

The optimisation framework developed is verified using a diverse set of tests, which confirm the right implementation of the units and the correct functioning of the constraints described in section 3.4. From every optimisation, the parameters used, the decision variables and the unit results, including their respective cost and emissions, are saved to ensure the traceability of the results and to allow model verification. The main verification tests are described in this section.

First, the technological definitions of the units are verified. The specific values of the in and outgoing resource streams, if possible, and the specific cost and emission values at unit load are calculated by hand and compared with the output optimisation data. The ratios between specific cost and resource stream magnitude are compared with values from the literature to validate the implemented technology characteristics. Furthermore, by implementing dummy demands for the units in OSMOSE, the correct functioning of the units within the optimisation environment is confirmed. For models depending on varying input profiles, such as the solar radiation for the PV, it is checked whether the output streams correctly reflect the input profile.

Furthermore, the balance of resources in the optimisation framework is verified. First, dummy demands are implemented for the different layers, which allows to trace the decisions in terms of units implemented. It is verified whether all units are supplying their respective demand, whether the streams are correctly connecting the units and whether the scales of the streams are coherent. Varying configurations of technologies are tested to ensure that no model deficiencies prohibit using specific technology configurations. Moreover, to verify the superstructure's robustness, it is exposed to extreme conditions, such as having no connection to external resources.

In addition to verifying the correct implementation of the technologies, the units' costs and impact definitions are verified. With the installed unit loads obtained from the optimisations and the specific cost and impact definitions, the overall system costs and impact can be confirmed for simple configurations in which the computations are traceable. It is verified whether the overall yearly costs are correctly computed from the results of the typical days. Furthermore, it is confirmed that the varying electricity prices and assigned grid emissions are rightfully used to determine the system's operating cost.

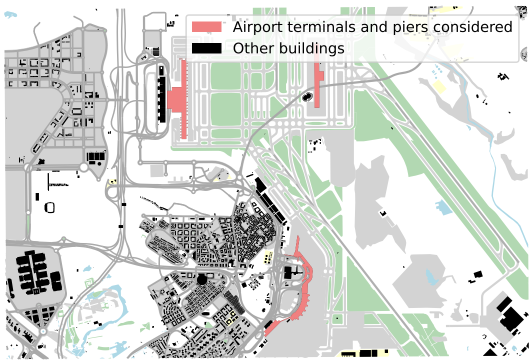
Most attention is needed to verify the correct working of the storage units. Simple test cases using only two periods with a small number of time instances and pre-defined resource unavailability in certain time instances are constructed, which force the system to use the storage options and allow the verification of the storage levels at the end of each time instance by hand. Next, it is verified that the installed storage capacity is adequate for receiving the allocated energy. When extending the periods to the full 12 typical days, the functioning of the storage units under extreme conditions, such as, for example, including full periods without electricity supply, wind and solar radiation, is verified.

B Input Data for European Hub Airports

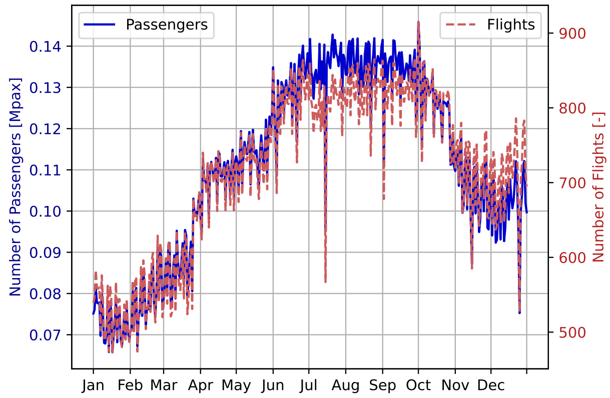
In section 4, the input data for the case-study of Amsterdam Schiphol airport and the energy demand profiles for the six European hub airports are displayed. This appendix displays the input data including the considered buildings as well as the passenger, flight, weather, electricity and input energy demand profiles for the five other

European hub airports, which are Madrid Barajas in section B.1, Munich in section B.2, Oslo-Gardermoen in section B.3, Rome-Fiumicino in section B.4 and Zurich in section B.5.

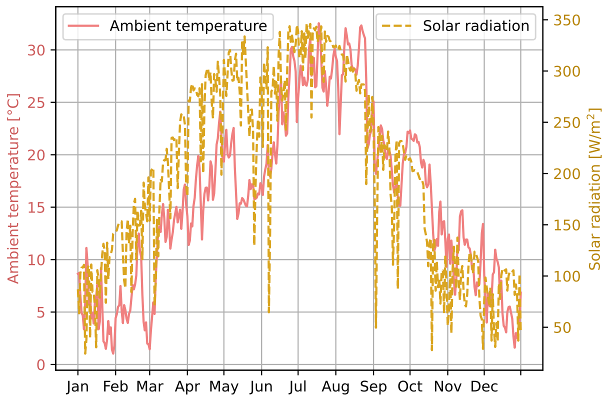
B.1 Madrid Barajas



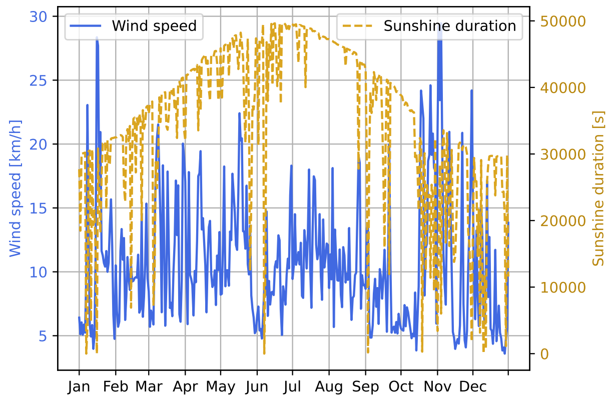
(a)



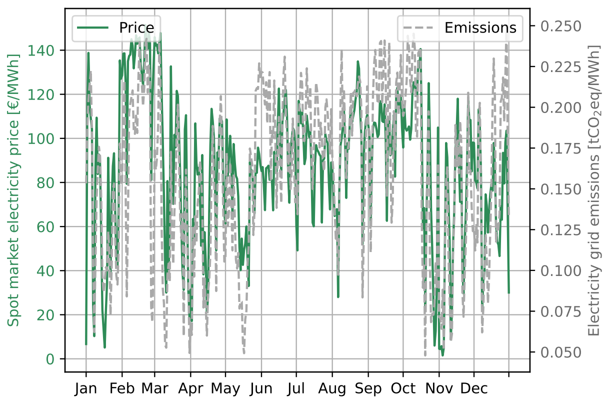
(b)



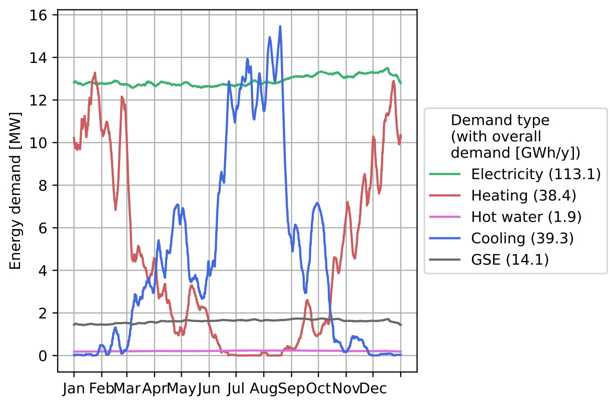
(c)



(d)



(e)



(f)

Figure B.1: Input data for Madrid-Barajas in 2023 including (a) the map of the considered terminal and pier buildings (using data from [74]), (b) the number of flights [86] and passengers (monthly passenger numbers from [141]), (c) the temperature and solar radiation [88], (d) the wind speed and sunshine duration [88], (e) the electricity price [90] and emissions (average yearly emissions per kWh from [91], yearly profile of renewable energy share from [90]) in Spain and (f) the estimated energy demand profiles

B.2 Munich

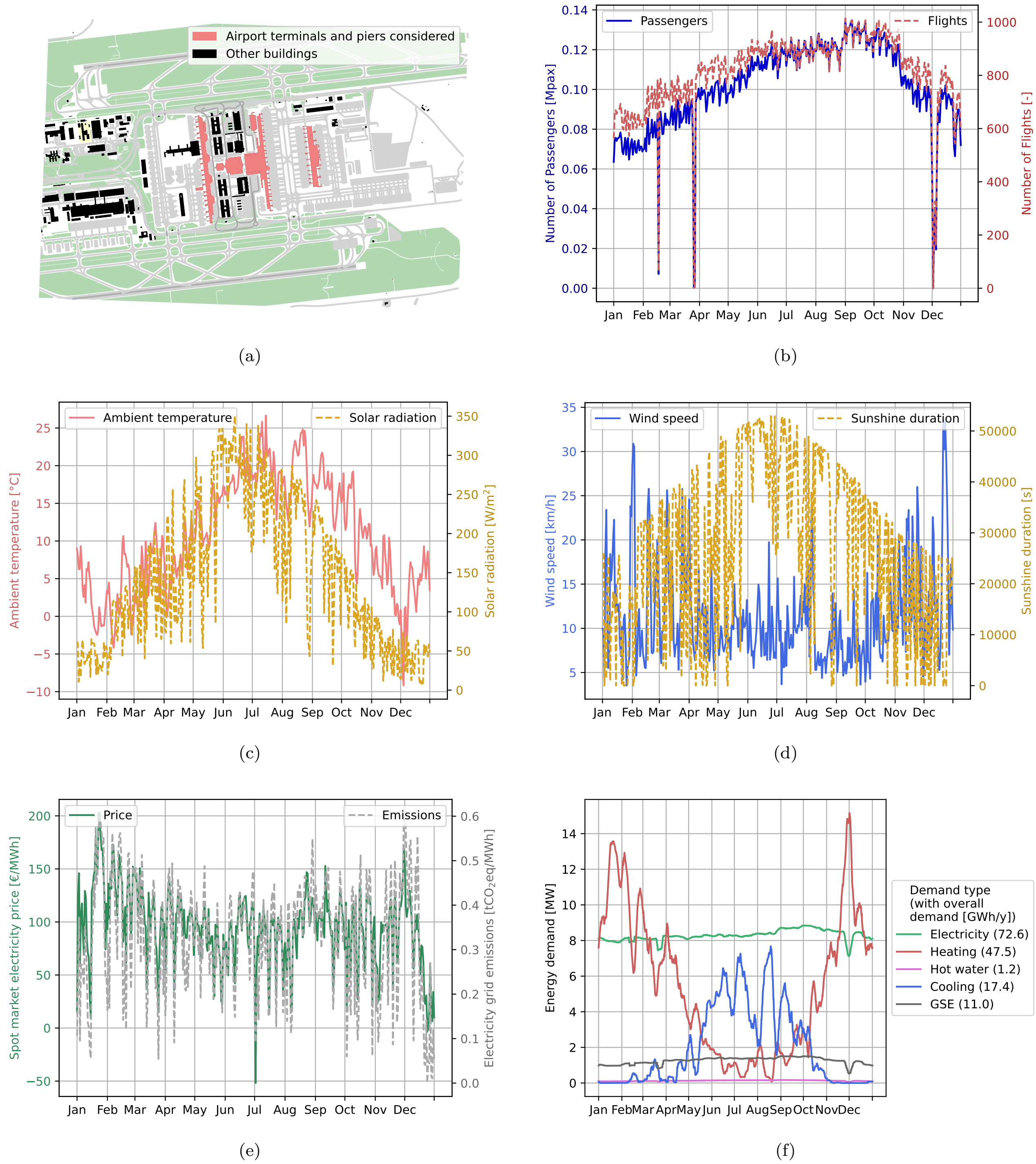


Figure B.2: Input data for Munich in 2023 including (a) the map of the considered terminal and pier buildings (using data from [74]), (b) the number of flights [86] and passengers (monthly passenger numbers from [142]), (c) the temperature and solar radiation [88], (d) the wind speed and sunshine duration [88], (e) the electricity price [90] and emissions (average yearly emissions per kWh from [91], yearly profile of renewable energy share from [90]) in Spain and (f) the estimated energy demand profiles

B.3 Oslo-Gardermoen

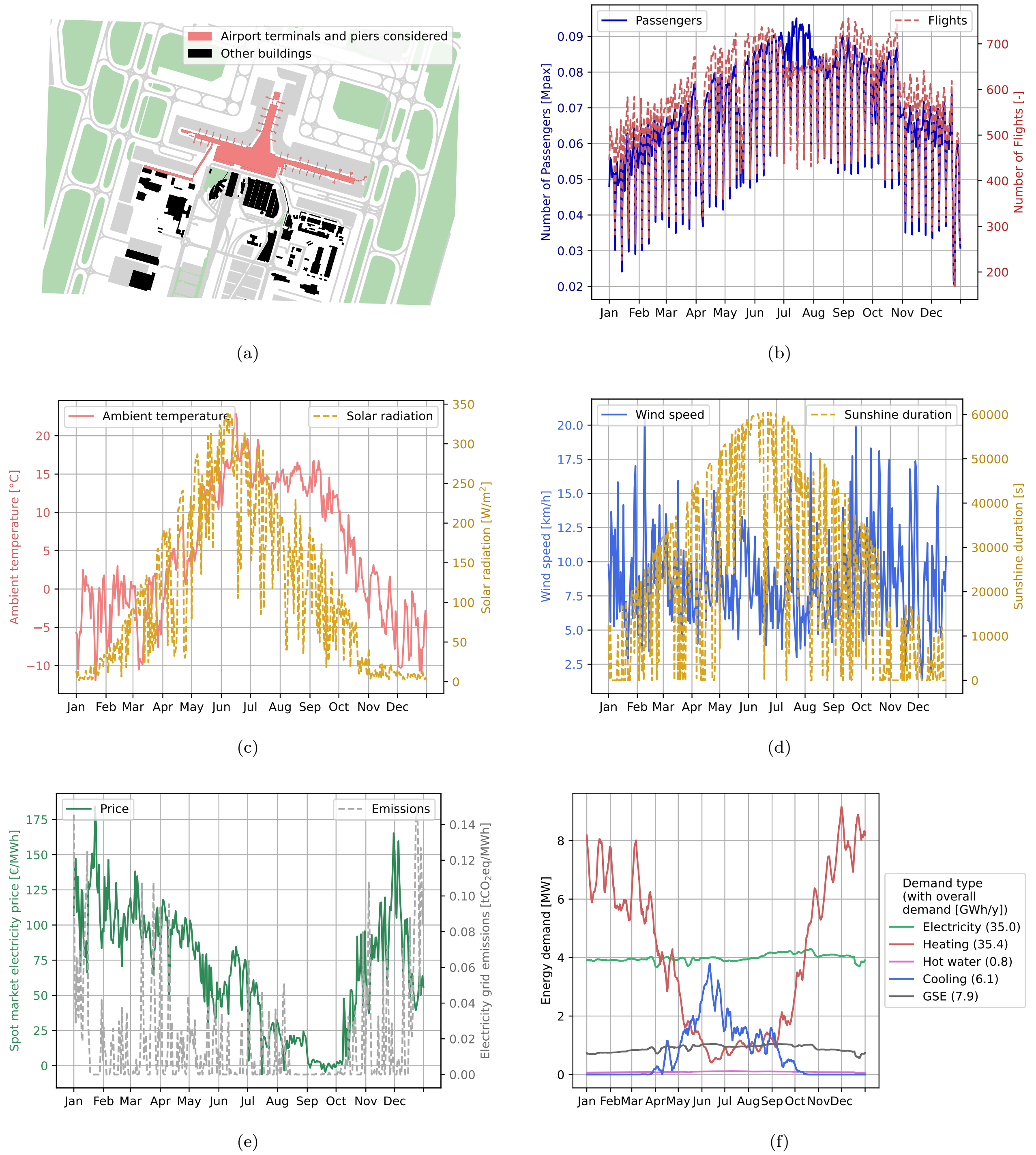


Figure B.3: Input data for Oslo-Gardermoen in 2023 including (a) the map of the considered terminal and pier buildings (using data from [74]), (b) the number of flights [86] and passengers (monthly passenger numbers from [143]), (c) the temperature and solar radiation [88], (d) the wind speed and sunshine duration [88], (e) the electricity price [90] and emissions (average yearly emissions per kWh from [155], yearly profile of renewable energy share from [90]) in Spain and (f) the estimated energy demand profiles

B.4 Rome-Fiumicino

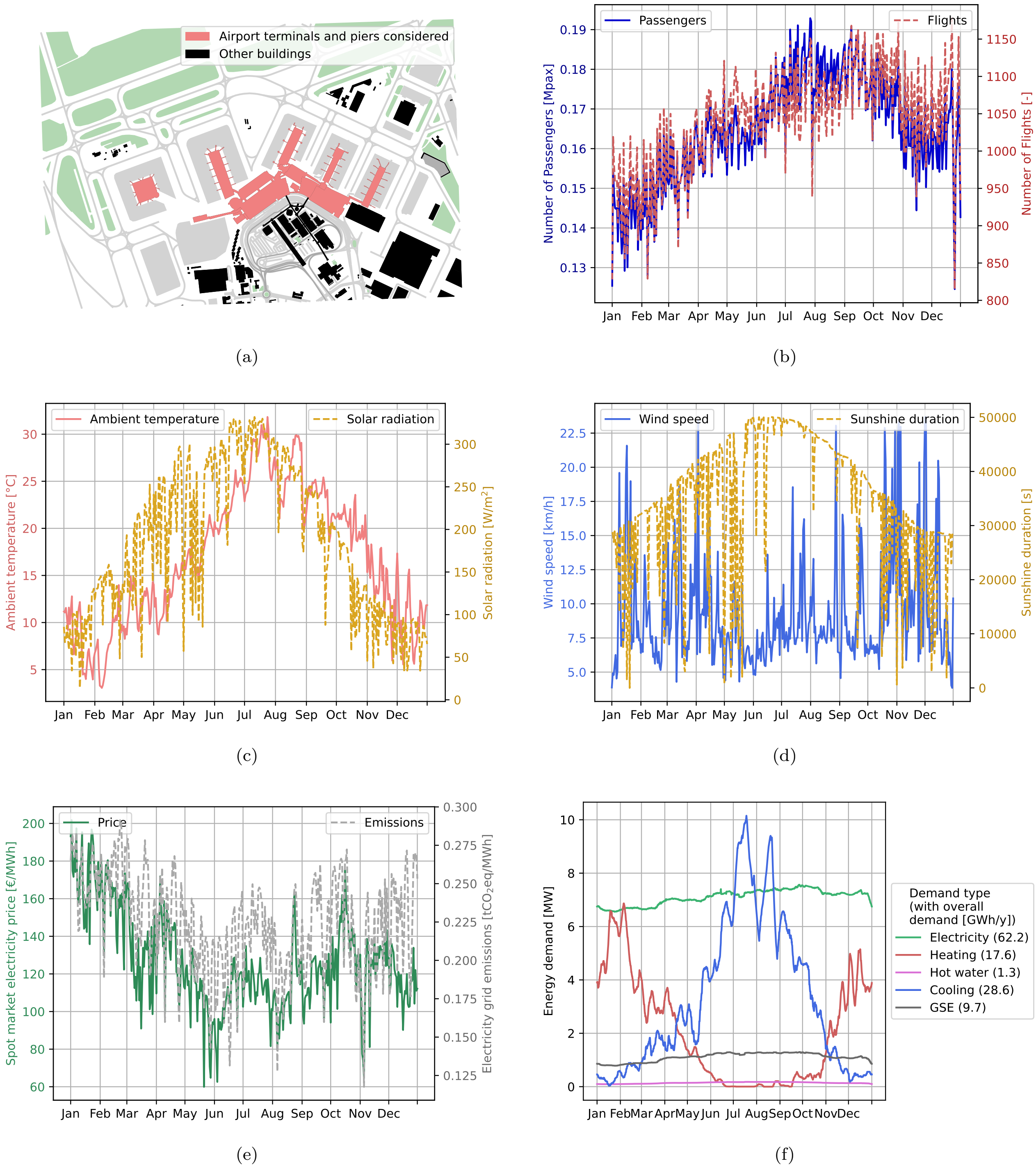


Figure B.4: Input data for Rome-Fiumicino in 2023 including (a) the map of the considered terminal and pier buildings (using data from [74]), (b) the number of flights [86] and passengers (monthly passenger numbers from [144]), (c) the temperature and solar radiation [88], (d) the wind speed and sunshine duration [88], (e) the electricity price [90] and emissions (average yearly emissions per kWh from [91], yearly profile of renewable energy share from [90]) in Spain and (f) the estimated energy demand profiles

B.5 Zurich

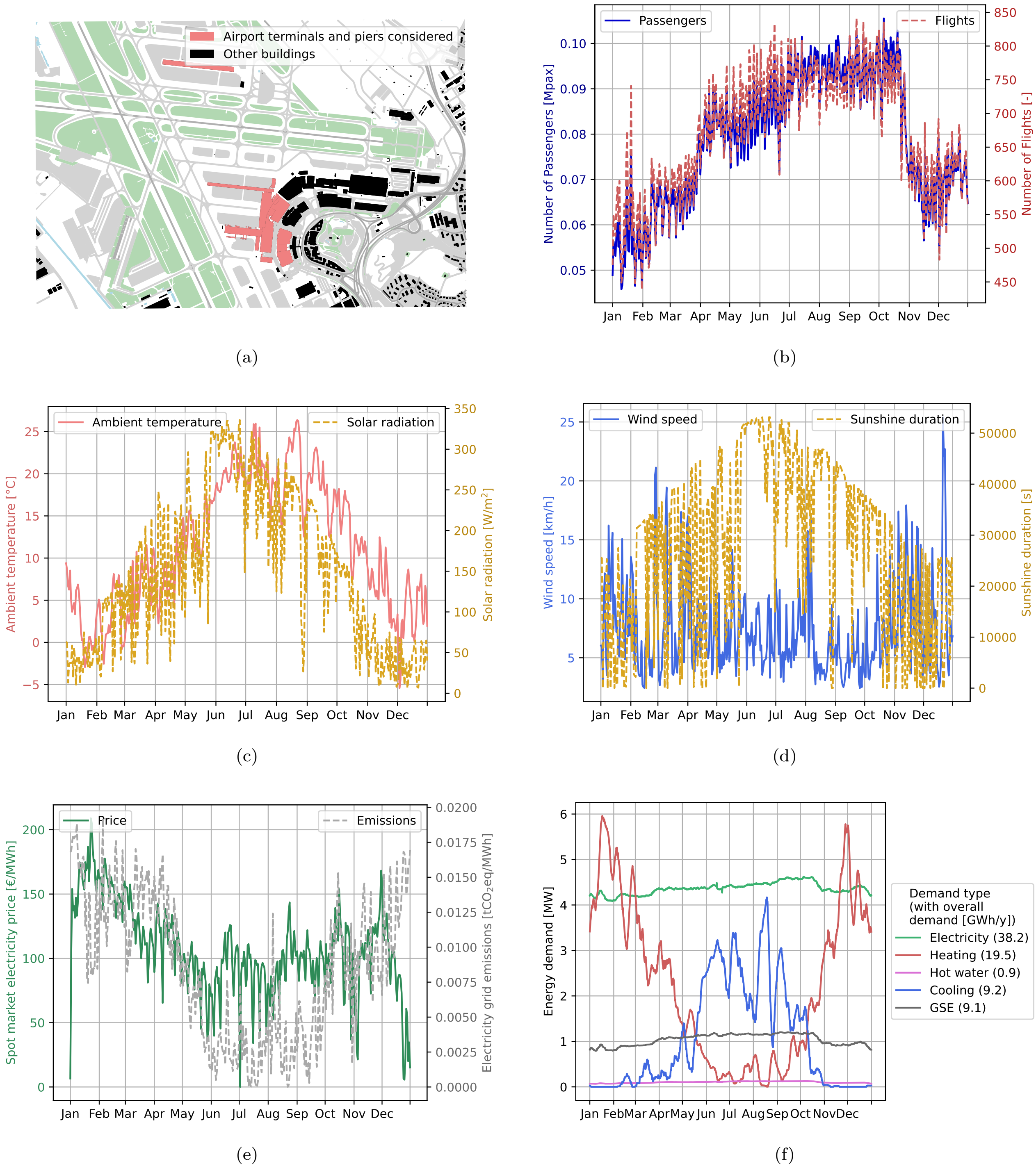


Figure B.5: Input data for Zurich in 2023 including (a) the map of the considered terminal and pier buildings (using data from [74]), (b) the number of flights [86] and passengers (monthly passenger numbers from [145]), (c) the temperature and solar radiation [88], (d) the wind speed and sunshine duration [88], (e) the electricity price [90] and emissions (average yearly emissions per kWh from [156], yearly profile of renewable energy share from [90]) in Spain and (f) the estimated energy demand profiles

C Capacities of Technologies Installed

In this appendix, the technology capacities are shown which are obtained from the optimisations for the selected configurations for Amsterdam Schiphol in section 5.1 and for the five other European hub airports in section 5.3. They can be found in the tables in section C.1 and section C.2 respectively.

C.1 Energy System Optimisation Amsterdam Schiphol

Table C.1: Overview of the capacities for the installed technologies in the selected solutions for further analysis from the Pareto front in Figure 20

	Electricity generation and storage			**Heating and cooling**				**CO_2 network**						**Hydrogen technologies**				
	PV (solar cell area)	**Mini wind turbine** (number wind turbines)	**Battery** (electricity stored)	**Boiler natural gas** (heat produced)	**Combined cycle natural gas** (electricity produced)	**Heat pump** (electricity used)	**Chiller** (electricity used)	**Central plant winter** (electricity used)	**Central plant summer** (heat exchanged)	**Distribution pipes** (length pipes and excavation)	**Air conditioning** (heat exchanged)	**Refrigeration** (electricity used)	**Heating** (electricity used)	**AEC** (electricity required)	**PEM** (electricity required)	**SOEC** (electricity required)	**SOFC** (electricity produced)	**Hydrogen tank** (H_2 stored)
	km^2	-	MWh	MW	MW	MW	MW	MW	MW	km	MW	MW	MW	MW	MW	MW	MW	MWh
BOI+CHI	0	0	0	16.88	0	0	11.77	0	0	0	0	0	0	0	0	0	0	0
CC+BOI+CHI	0	0	0	9.3	9.02	0.11	11.77	0	0	0	0	0	0	0	0	0	0	0
HP+CHI	0	0	0	0	0	7.55	11.77	0	0	0	0	0	0	0	0	0	0	0
PV+CO_2N	0.15	0	0	0	0	0	0.15	0.74	12	11.54	5.87	2.23	3.68	0	0	0	0	0
PV+CC+CO_2N	0.13	0	0	1.05	10.9	0	0	0	12.21	11.54	8.79	2.21	1.38	0	0	0	0	0
PV+WT+CO_2N	0.74	2534.37	0	0	0	0	7.79	1.17	2.81	11.54	4.88	0.42	3.68	0	0	0	0	0
BAT+PV+CC+CO_2N	0.14	0	9.39	1.66	10.11	0	0	0.16	12.21	11.54	8.04	2.21	1.27	0	0	0	0	0
BAT+PV+CO_2N	0.21	0	50.55	0	0	0	0	0.71	12.21	11.54	5.87	2.26	3.68	0	0	0	0	0
XBAT+PV+CC+CO_2N	0.37	0	146.18	0.38	6.88	0	0	0.56	12.21	11.54	2.39	2.22	2.25	0	0	0	0	0
XBAT+PV+CO_2N	0.9	0	198.73	0	0	0	0	1.06	12.21	11.54	5.87	2.26	3.68	0	0	0	0	0
H_2S+PV+CC+CO_2N	0.53	0	0	0.05	10.72	0	0	0.38	15.22	11.54	13.97	2.08	1.98	18.89	0	0.32	4.76	104.68
XH_2S+PV+CC+CO_2N	1.13	0	0	0.25	8.86	0	0	0.47	26.73	11.54	21.77	1.88	1.77	66.64	0	1.57	15.46	276.88
Independent energy system	1.02	4032.54	296.25	0	0	0	0	0.99	12.21	11.54	5.87	2.26	3.68	0	0	0	0	0

C.2 Energy System Optimisation of Other European Airports

Table 2: Overview of the capacities for the installed technologies in the selected solutions for further analysis from the Pareto front in Figure 20

		Electricity generation and storage			**Heating and cooling**				**CO_2 network**					
		PV (solar cell area)	**Mini wind turbine** (number wind turbines)	**Battery** (electricity stored)	**Boiler natural gas** (heat produced)	**Combined cycle natural gas** (electricity produced)	**Heat pump** (electricity used)	**Chiller** (electricity used)	**Central plant winter** (electricity used)	**Central plant summer** (heat exchanged)	**Distribution pipes** (length pipes and excavation)	**Air conditioning** (heat exchanged)	**Refrigeration** (electricity used)	**Heating** (electricity used)
		km^2	-	MWh	MW	MW	MW	MW	MW	MW	km	MW	MW	MW
Battery for energy storage and all non-storage technologies	**EHAM**	0.14	0	9.39	1.66	10.11	0	0	0.16	12.21	11.54	8.04	2.21	1.27
	LEMD	0.17	0	10.56	2.03	12.90	0	0	0	26.49	12.56	11.89	3.76	1.64
	EDDM	0.11	0	3.96	4.57	9.51	0	0	0.32	15.83	14.37	5.96	2.56	2.03
	ENGM	0.05	0	0	2.74	5.38	2.66	6.28	0	0	0	0	0	0
	LIRF	0.12	0	4.70	1.80	8.05	0	0	0	15.23	11.37	7.28	2.54	0.58
	LSZH	0.07	0	0.83	1.28	5.08	0	0	0.04	7.77	6.09	3.66	1.24	0.79
Battery for energy storage and only renewable technologies	**EHAM**	0.21	0	50.55	0	0	0	0	0.71	12.21	11.54	5.87	2.26	3.68
	LEMD	0.25	0	65.61	0	0	0	0	0.59	26.49	12.56	7.85	3.83	4.86
	EDDM	0.17	0	43.16	0	0	0	0	0.97	16.40	14.37	4.84	2.09	5.23
	ENGM	0.04	0	0	0	0	0	0	0.56	6.60	7.90	3.51	0.80	2.86
	LIRF	0.23	0	56.37	0	0	0	0	0.40	15.23	11.37	4.18	2.59	2.68
	LSZH	0.10	0	13.35	0	0	0	0	0.36	7.77	6.09	3.28	1.26	2.10

II

Literature Study

1
Introduction

Airports are complex infrastructures. Many different stakeholders are involved in the operation of airports, and thus, many different parties require energy at an airport. Consequently, optimising an airport's energy systems involves different considerations when defining the demand, choosing energy technologies and setting up the requirements. The literature review aims to give an overview of relevant work for energy systems of airports. In this Chapter 1, the airports with their stakeholders and division in space are introduced. Next, Chapter 2 gives an overview of the energy demands at an airport. Chapter 3 then explains what studies have already been performed related to airport energy system optimisations. Subsequently, Chapter 4 presents possible technologies to be used with their advantages and disadvantages. Finally, Chapter 5 ends with identifying the research gap for this study and Chapter 6 outlines the research.

1.1. Characteristics of an Airport

Aviation is one of the most important drivers of globalisation, and cities with large airports or, even hub airports are often important economic centres [4]. Airports thus play a key role in the transportation system in the 21st century. An airport is defined as "a place where aircraft regularly take off and land, with buildings for passengers to wait in" [5]. The busiest airport in the world is Atlanta (USA), which was employed by 104.6 million passengers in 2023 [6]. Airports accommodate up to 775,000 aircraft movements per year, with again Atlanta (USA) being the busiest airport in 2023 [6]. Finally, they move up to 4.3 million tons of freight per year, with Hongkong (China) leading this statistic in 2023 [6].

Due to the considerable number of passengers, freight, and aircraft that are moved, different stakeholders are involved in an airport. These range from the passengers departing or arriving to the federal government where the airport is located [2]. The first group of stakeholders are the passengers, who are interested in on-time flights, smooth operation, and good and diverse services [2]. Their interests are more personal, except for the interest of having a connection hub that offers a diverse set of destinations. On the other hand, there are air carriers and general aviation, which are the direct users of the airport. They are concerned that the needs of their passengers and clients are satisfied while paying low operation costs and ensuring the safety of their operation [2].

The third group of stakeholders are not customers but the airport itself or service providers located at the airport. They want to satisfy all needs of passengers and air carriers to stay attractive compared to other airports and to increase the number of passengers while also maximising revenue and increasing environmental sustainability [2]. They must do this by ensuring the infrastructure is up to current standards and the employees are well-trained and satisfied [2]. Next, there are multiple stakeholders providing services at the airport, such as restaurants, parking operators, providers of transportation at the airport or service providers for the air carriers, which are interested in the growing number of passengers but also minimum fees they need to pay to the airport [2].

Finally, there are many outside stakeholders who also have interests related to airport activities. First, investors [2] who desire optimal (economical) performance and growth in terms of passengers and revenue. Organisations and communities in the region, as well as local and federal governments, want a maximum number of destinations, an airport up to the current technological standards, the possibility for growth and safe operation [2]. However, communities, local governments and environmental NGOs also desire minimum noise pollution and emissions and, thus, a minimum impact of the airport on the environment [2].

Overall, the goals of the different stakeholders range from an efficient and smooth operation of the airport, minimal costs, growing passenger numbers, economic growth and maximum revenue to a minimised impact of the airport on its environment.

Due to the large number of stakeholders involved, an airport structure is very complex, containing several facilities. An exemplary layout is shown in Figure 1.1 [7]. As can be seen in the figure, the airport can be divided into two different parts: the landside area (coloured in red) and the airside area (coloured in orange) [8]. The landside area primarily includes all areas where passengers or freight move. They, for example, contain passenger terminal buildings, freight terminals, parking lots, railway stations, etc. [9]. The airside area consists of the areas where aircraft are moving. It includes, for example, the terminal airspace, the aircraft stands, taxiways, and runways [9].

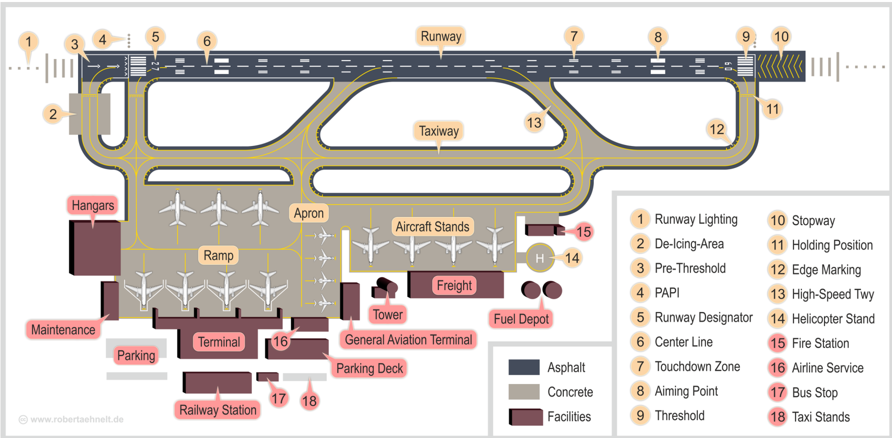


Figure 1.1: Typical airport infrastructure layout, not up to scale (Reproduced from [7])

2
Airport Energy Demands

The extensive range of stakeholders and numerous facilities at an airport result in significant energy consumption. In fact, Schiphol airport consumes an equivalent amount of electricity to that of 50000 households [10], thus being equal to the electricity consumption of a small city. Considering that most energy consumed at the moment is still non-renewable, this leads to a considerable potential for reducing the environmental impact of an airport.

The environmental impact of an airport can be reduced by employing different strategies. First, the energy demand can be reduced through efficient and optimised operation. Corlu et al. [11] studied different options for optimising the energy consumption in transportation systems. For air transportation, the most significant reductions can be achieved through aircraft trajectory optimisations and airport ground operations, such as taxiway optimisation, runway scheduling, or integrated approaches. Operational changes can be implemented quickly and lead to fast reductions in energy consumption.

The second option for reducing the environmental impact of an airport requires the introduction of new technologies. As can be seen in Figure 1.1, airports have many different facilities, all consuming energy and resources. Greer et al. [12] thus suggested the introduction of renewable electricity sources, the deployment of electric vehicles and equipment, efficient water management, the introduction of energy-efficient fixtures as, for example, light emitting diodes or the choice of durable materials in construction to make an airport more sustainable. This could come along with an efficient and optimised renewable energy system design.

Before optimizing and reducing an airport's energy consumption, it is crucial to understand its energy needs. This section explains the energy demand of an airport by first providing an overview of the energy demand at European airports in Section 2.1. Section 2.2 then illustrates the characteristics of energy demand using specific airports as examples. Section 2.3 discusses how to determine the overall energy demand of an airport. Next, Section 2.4 explains the specific energy demands in different areas of the airport. Finally, Section 2.5 defines the main influencing factors, and Section 2.6 presents methods for quantifying energy consumption and its impact.

2.1. Overview of Energy Consumption of Real Airports

Energy consumption significantly varies between different airports. It is hard to compare the specific consumptions, as the metrics provided by airports are varying, and often, little data is available. The main parameters that can be found for most airports are the total yearly energy consumption, the number of aircraft movements at an airport, and the total number of passengers per year, the latter two being correlated with each other. The energy consumption is plotted against the passenger numbers in 2.1. It must be noted that not only the consumption of individual airports but also of airport groups, such as, for example, the Spanish airports of AENA and the Aéroports de Paris, both operating more than 20 airports, are given. This leads to points with significantly higher energy consumption, movement and passenger numbers than the average, but the specific energy consumptions are comparable.

From Figure 2.1 it can be observed that there are a few outliers with a high yearly energy consumption, most notably the airports of Milan (yearly total energy consumption of 452 GWh) and Munich (387 GWh). This could be explained by different definitions of what is included in the overall energy con-

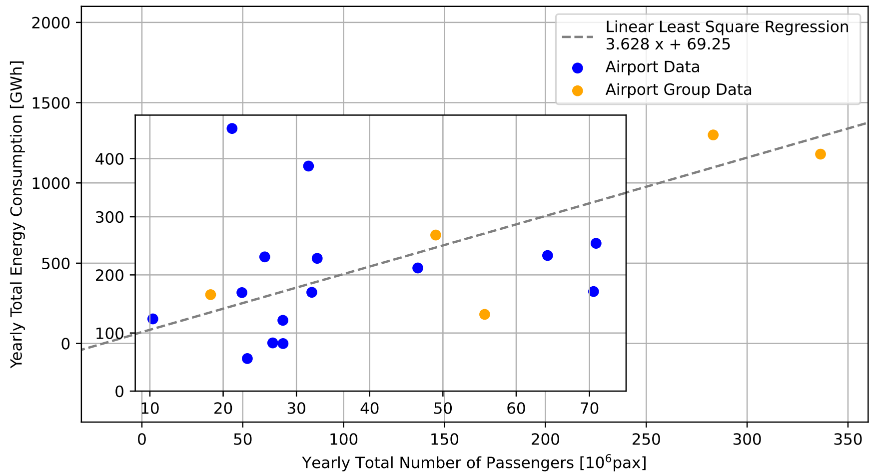


Figure 2.1: Yearly total energy consumption of 20 large European airports and airport groups vs. number of passengers at airport [13]–[36]

sumption and by the use of different energy resources with lower efficiencies. In general a linear trend can be observed for the yearly total energy consumption with respect to the number of passengers. The same trend can be observed when plotting the yearly energy consumption with respect to aircraft movements.

2.2. Characteristics of Energy Consumption of Real Airports

Having seen the overall energy consumption of different airports, the different usages of energy as well as the resources consumed can be analysed. For both of these aspects, available data is quite different for every airport, and only a few of them provide detailed information. Regarding the usage of energy, six airports provide more detailed data on how much energy is consumed for heating, cooling, as electricity or as fuel [15]–[17], [19], [20], [25]. As a first trend, it was observed that electricity usage is the most important energy consumer with approximately 57%, followed by heating usage with approximately 31% and cooling and fuel usage both with approximately 12%. However, those numbers must be used with caution due to the possibly different definitions of usage for the different airports.

Next, the resources consumed by the energy system were analysed. Again, only for six airports detailed data on the consumption of resources was found [13], [14], [18], [21], [27], [28]. The results are shown in Figure 2.2. Significant differences can be observed for the airports. At Frankfurt airport, 69% of all consumed energy resources are diesel, while it only has a minor share in all other airports. In Munich and Milan, more than 72% of the consumed energy is natural gas. Istanbul, Athens and Portuguese airports rely mostly on electricity for the energy resources they consume, representing approximately 63% to 79% of the consumed resources. Again, it must be noted that these results should be interpreted carefully, as the way the data is provided differs by every airport.

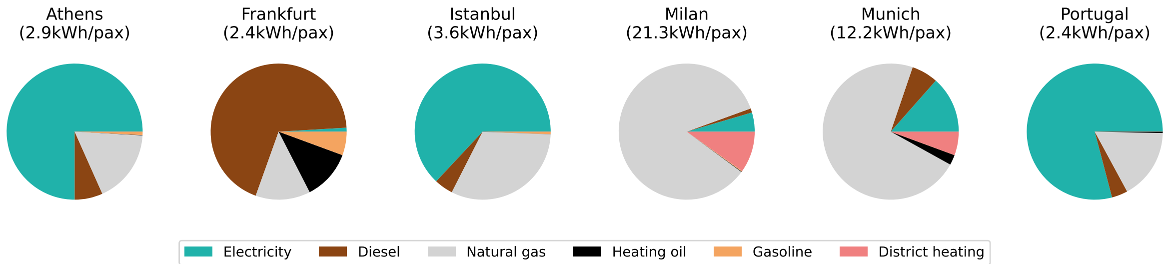


Figure 2.2: Comparison of indicated energy resource consumption distribution and consumption per passenger at different European airports [13], [14], [18], [21], [27], [28]

One last metric which is given for many airports is the share of renewable energy used at an airport. For the analysed airports, this varied from approximately 15% at Zurich airport [15] to approximately 80% for the airports in Spain [25]. However, also these values must be taken with caution: for the Spanish airports, it has, for example, been assumed that the electricity is guaranteed to be 100% renewable [25], whereas in Zurich, only 28% of the consumed electricity was considered to be renewable [15]. Overall, the importance of providing consistent metrics for the energy consumption of all airports was observed, as the results were difficult to compare and are difficult to use as a general base of comparison for later obtained results.

2.3. Determining Overall Airport Energy Demand

In Section 2.1, the energy demand for 20 of the largest European airports or airport groups was presented. A trend in energy demand per passenger and air movement was observed, though there were still significant differences between the different airports.

A similar study was performed by Costa et al. [37], where the energy consumption of European airports in 2012 was reviewed. In this study, data was obtained for 51% of the 113 studied sites. Significantly different energy consumptions were observed, but an average of 9.29kWh/passenger/year was obtained, which is slightly higher than for the average airports shown in Figure 2.1. It was also observed that larger airports such as Heathrow, Charles de Gaulle or Frankfurt have 50% or 100% higher energy consumption per passenger than smaller airports. Possible improvements identified were replacing lighting technologies, improving the heating, ventilation and air conditioning (HVAC) system, which causes 80% of the energy consumption and implementing renewable energy technologies.

Overall, airports have a wide range of different facilities with different energy demands. The PhD-thesis written by Ortega Alba [38] analysed in detail the different energy demands at the Santander Airport in Spain. It explained and defined the energy demand in three steps. First, it characterised the airport based on general administrative, statistical or meteorological parameters and overall information on the airport, its management and its operation characteristics. In the second step, energy data was analysed by identifying and classifying the main energy users of the airport and by defining an energy inventory and balance. Finally, in the third step, the electric pattern is described. For this, general, hourly, weekly, monthly, seasonal as well as yearly energy demands were analysed, and profiles were obtained. Several concepts were employed to characterise the airport's energy demand. The energy demand was divided into airside and landside demands. The airside part of the airport is the part where the passenger is the primary customer, whereas on the airside part, the aircraft and its related activities are the primary customer. Energy demands in both parts could be further subdivided into different clusters and demands, such as lighting, data processing, HVAC, signalling and information, etc. It was found that the energy demand is independent of the day in the week but that the time during the day and the season have a significant impact.

Another study defining the overall energy demand of an airport was the Master's thesis written by Radhakrishnan [39] on the energy system of Stavanger airport in Norway. In this study, the energy consumption, distribution and demand of the airport were determined and compared with the theoretically required energy for electric aviation. It was found that the demand for electric aviation is significantly higher than the demand for the airport itself. Photovoltaic cells (PV) were found to not be enough to provide all the electricity required, and correct placement and inclination of the PV were identified to be important. Batteries and hydrogen storage were observed to be unprofitable, as it is cheaper to sell and buy electricity from the grid, even if the energy demand in winter is significantly higher than in summer. Finally, energy management measures, such as insulation, were also important and could lead to a reduction of energy consumption of up to 25%.

Rubeis et al. [40] analysed the energy consumption, including electricity, thermal energy and fuels, of Leonardo da Vinci International Airport in Rome. For their approach to implementing an energy management system, they determined both the energy production as well as the consumption in different airport areas (terminaly, offices, runways, etc.) for the three different demand types. This allowed to obtain a detailed division of the energy consumption and to assess significance of the different energy consumers. Important monthly variations were observed in energy consumption, with peak electricity consumption during summer due to air conditioning and thermal demand during winter due to heating demands. Furthermore, improved energy management was observed to reduce electricity demand, whereas the thermal demand increased with an increasing number of passengers. Different technologies were proposed for the energy system, such as a high concentrator solar plan, mini and micro wind turbines and electrochemical storage and a Smart Grid system was optimised for load management. It was suggested to apply similar energy system solutions also for other European airports.

2.4. Demands of Different Airport Areas

The energy demand of an airport is composed of several components. From the previous studies, the following three main demands were observed: electricity, thermal energy for heating and cooling and fuel. Another option for dividing the demand is to only consider the demand of specific sub-areas of the airport. This was done in several studies considering, for example, the energy demand of airport buildings, airport operations, etc. Most importantly, the energy demand can be divided into activities taking place on the landside and airside area of an airport, as was explained in Section 1.1.

Figure 2.3 attempts to give an overview over all energy demands which were identified in different studies [38], [40]–[43]. They are clustered into four main groups: buildings, vehicles, aircraft and ground. Each of the group is then split into smaller sub-groups with similar energy usage characteristics. Every sub-group is categorised in either landside or airside energy demands. For all sub-groups, an overview of the included activities/facilities is given as well as a summary of the types of energy demands.

2.4.1. Landside Area

As could be observed from S. Ortega Alba [38], the largest contribution of the landside energy demand comes from the terminal buildings. The study divided this demand into different demand sources, which are heating, ventilation and air conditioning, lighting, information and communication technology, data centres, signalling, security, electromechanical and other various equipment around the airport. Next to the terminal buildings, parking and urban zones were observed as the second consumer on the landside area. Similar observations can be made from de Rubeis et al. [40], where the most significant energy consumption at the airport was observed from the terminal buildings.

From Xianliang et al. [44], the cooling plant as well as the HVAC system were observed to have the most important contribution towards the terminal building energy demand, making up approximately 32% and 17% of the total energy consumption. They were followed by offices and commercial areas with approximately 13% and 11% of the total energy consumption. Lighting, advertising, elevators, boarding bridges, the luggage system, etc., only displayed minor energy consumption contributions. When comparing the different energy demands, the HVAC system had an uneven distribution of consumption in space and time and was influenced by several factors, for example, the meteorological data or the flow of passengers, the former explaining also the important contribution of the cooling plant, as the studied airport was located in a warm climate zone.

The demand on the energy system can be lowered by applying methods of energy consumption reduction. Yildiz et al. [45] studied different options, which allowed the reduction of both the consumption and the emissions of the airport terminal building. In the studied airport, the HVAC system was observed to have the most important contribution to the overall consumption. Promising reduction strategies concern this system, such as improving the system's efficiency, changing the setpoint temperature, installing additional heat exchangers, or replacing the circulation pumps.

Next to the buildings with heating, cooling, ventilation, air conditioning, lighting and various other demands spread over the building, there are individual systems with very specific energy demands on the landside area of the airport. One of them is the baggage handling system, which energy consumption is analysed in multiple studies. Kierzkowski and Kisiel [46] created a simulation model of the check-in part of the baggage handling to determine its energy consumption, which is dependent on the structure of the baggage handling system, the flight timetable and the allocated resources for each flight. The baggage handling system was also an object of analysis for Lodewijks et al. [47], who observed that with an optimised baggage handling system and specially optimised operations, CO_2 emissions could be reduced substantially. Those small models modelling individual subsystems could be used as modules for an extended model of the energy consumption of the airport systems [46].

2.4.2. Airside Area

The second part of an airport is the airside area, which is primarily characterised by the vehicles operating on the taxiways, aprons and around the gates. Several types of vehicles operate in an airport,

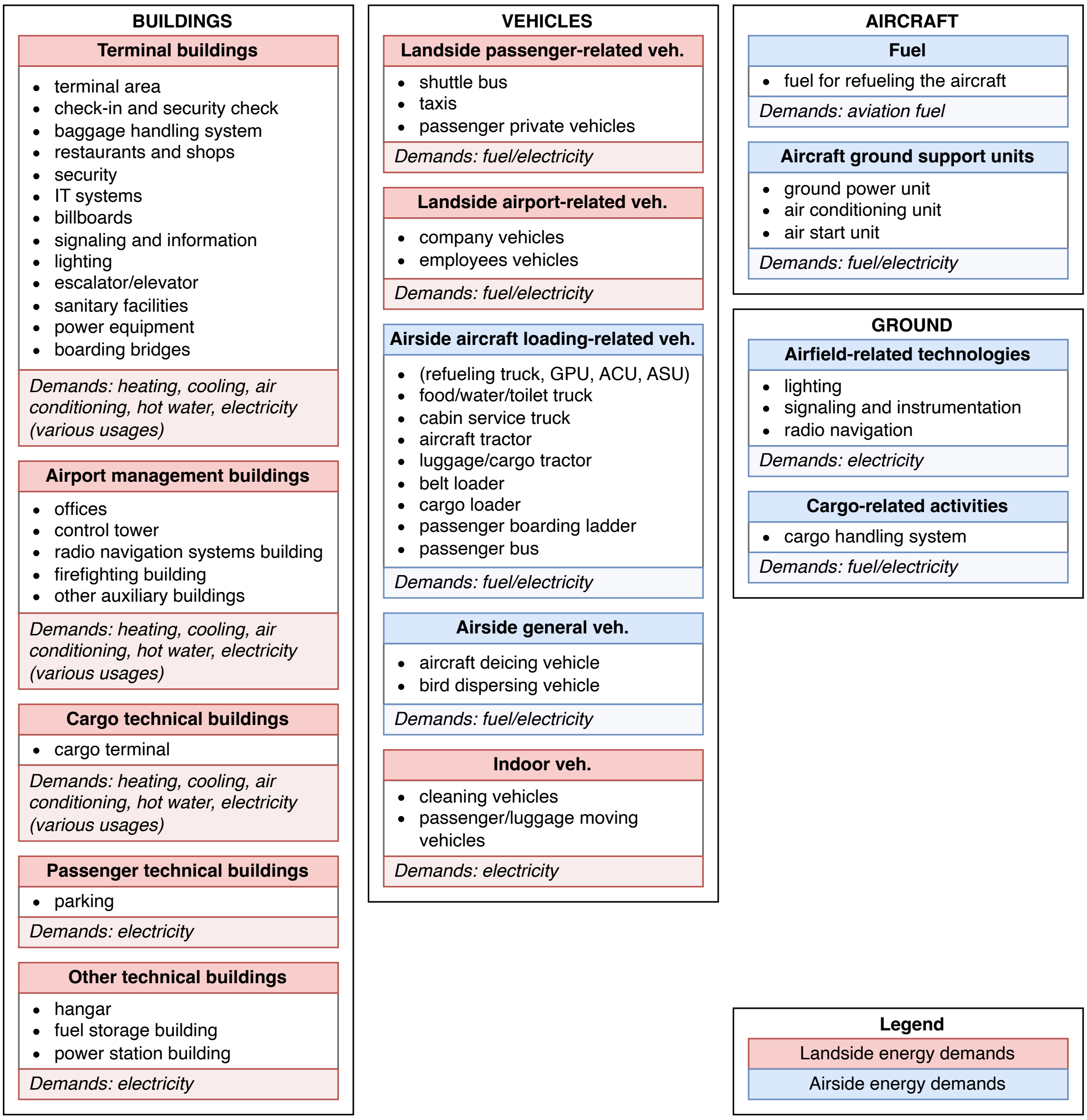


Figure 2.3: Overview of airport energy demands retrieved from literature review [38], [40]–[43]

most of them in the airside area, as it can be seen in Figure 2.4 [42]. The vehicles found at the landside area are mostly related to the travel of the passengers to the airport or to the commute of the airport employees. On the other side, vehicles in the airside area of the airport are related to loading the aircraft, towing the aircraft, preparing the aircraft for take-off or for other tasks in the airside area.

The study performed by Liu et al. [42] performed an extensive investigation of the energy consumption of ground vehicles at the example of a Chinese airport. They observed that the electrification rate is twice as high for airside (25%) than for landside (12%) vehicles, while there are more landside than airside vehicles at an airport. Furthermore, they mention the important storage potential of airside vehicles, which could help achieve an airport energy system based on renewable resources. Vehicles on the airside part of the airport, in particular, have the potential for such a storage system, while the overall storage potential of all vehicles would be nearly sufficient for running the airport fully on solar energy.

Bao et al. [48] focused on one specific type of vehicle, the towing tractor, but suggested extending their model also to other ground support equipment types. They investigated the performance of a mixed fleet scheduling of both conventional and electric towing tractors, where the electric towing tractor was also assumed to be able to replace the aircraft auxiliary power unit (APU) while towing. The ideal

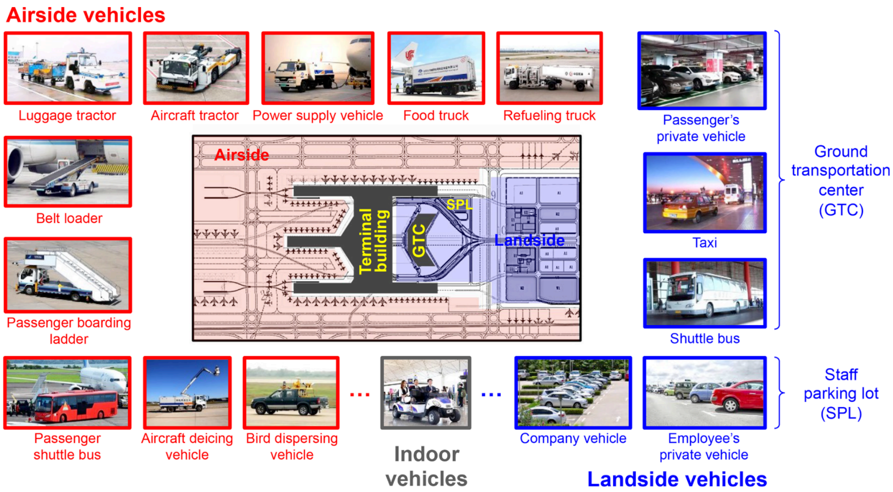


Figure 2.4: Ground vehicles which can be found normally at an airport in the airside and landside area (Reproduced from [42])

ratio between conventional and electric towing tractors, as well as the performance in terms of costs and flight delay, was observed to vary significantly based on the scenario, which is characterised, for example, by the distances to be driven and the number of flights to be served.

Multiple current projects focus on decreasing the energy demand of ground vehicles through efficient operation, routing and scheduling. An example of this is the study performed by Sigler et al. [49], which optimised the airport shuttle routes to operate them more energy efficiently. Optimisation of the shuttle routes allowed to achieve an energy reduction at the cost of an increased average passenger wait time. Another example is the fleet scheduling of electric towing tractors, as was done by Zoutendijk and Mitici [50]. While using more electric vehicles in order to reach climate targets, their electricity demand also increased. Thus, it is important to optimise the vehicle schedules to operate them under a limited electricity capacity. From the optimised schedules, they observed that the highest charging occurs between 15:00 and 17:00 when assuming regular operations. With increasing battery capacities, it was possible to only charge during the night, which, according to their results, saves 10% of the emissions, as no fast charging during the day is required.

2.5. Factors Defining Airport Energy Demand

Airport energy consumption is influenced by several factors. These can be the size of the airport, as is observed in Section 2.1, the flight schedule or the environment the airport is located in. For example, a correlation can be observed between the terminal area and the passenger flow, and they both also determine the overall airport energy consumption [51]. As expected, larger airports have higher energy consumption but typically lower consumption per passenger [52].

Li et al. [52] studied the influence of climate zones on airport energy consumption. The authors observed that the highest consumptions occur in freezing and cold climate environments. These are followed by airports located in climate zones with hot summers and cold winters, hot summers and warm winters and mild climates in this respective order. Overall, the energy consumption in a freezing and cold climate was two to four times higher than in mild climates. Comparable studies confirmed the observation that the highest energy consumptions occur in areas with hot summers and/or cold winters [51]. This can well be explained by the fact that heating and air conditioning represent around 35-50% of the overall airport energy consumption [51]. Costa et al. [37] furthermore suggested looking at weather data as an additional factor defining energy consumption.

Lin et al. [51] also looked at the energy consumption in different regions. For airports in Europe and Japan with an annual passenger flow higher than 10 million passengers, significantly higher energy consumptions were observed than for airports of the same size in China. Overall, energy consumption could be split into two parts: basic consumption, which is the energy required for the transportation functions of the building, and variable consumption, which is dependent on the climate and thus significantly varies between different airports.

Another determining factor is the spatio-temporal distribution of the passengers within the terminal.

Gu et al. [53] introduced a model which allows to estimate the number of people at different areas in the airport at different times, using a set of 14 different equations characterising the passenger distribution at different locations, such as the check-in area, the security check area, etc. Those distributions then allowed to calculate the energy demand for HVAC. 11.3% lower energy demands were obtained when applying the spatiotemporal model for designing the energy consumption, which showed the potential of adapting energy demand to the passenger distribution. However, the model was still limited to specific types of airports and needs to be extended to other airports that are different in terms of size or the processes to be globally applicable. Furthermore, the impact of baggage, the effect of passenger relationships, holidays or differences in queuing time can be considered to improve the model further.

2.6. Methods for Quantifying Airport Energy System

Different methods are observed to quantify the overall energy demand of an airport. When looking at the airport buildings, the energy consumption per unit area is often used and considered as the best indicator [51]. When looking at the overall energy consumption, it is often given per passenger. However, more methods for quantifying the energy consumption of airports could be beneficial. Most importantly, they need consistent and accurate measurement methods and uniform standards in the creation of statistics [52], in order to make the energy consumption results comparable between different airports and to create a base of comparison when developing new energy systems.

Greer et al. [12] looked at different metrics which are used to assess the environmental sustainability of an airport. The greenhouse gas emissions of the energy system are often employed to assess the environmental performance of an airport. Alternatively, there are however also other metrics: The LEED (Leadership in Energy and Environmental Design) is used to assess buildings and gives points to buildings based on their design, the materials used, etc. [12]. Moreover, the LCA (life-cycle assessment) considers the environmental impact from the extraction of materials for production up to the use of different components and can be used to assess different construction components of the airport, such as typically for the airport pavement but also for energy technologies [12].

3
State-of-the-Art of Airport Energy System Optimisation

Optimisation of energy systems for airports has already been performed in multiple studies. An overview of similar studies can be seen in Table 3.1. Most studies only focus on optimising the (terminal) building energy system, analysing how hybrid, renewable or combined heating, cooling and power energy systems are performing, whereas only a few studies treat the airport operations or the aircraft energy demands. As key performance indicators (KPI), mostly the overall or operational costs and/or the environmental impact are presented.

Table 3.1: Overview of studies on airport energy system optimisations

Case study	**Focus**	**Scope**			**Method**				**KPI shown**		
		Buildings	Operations	Aircraft	Model	Objective	Grid connection	Fossil fuels	Costs	Env. impact	Others
[41]	Energy system	Yes			MILP	Cost	Yes	Yes	Yes		
[54]	Hydrogen		Yes		MILP	Cost	Yes		Yes		Technology sizes
[55]	Hybrid energy system	Yes			HFSP	Cost	Yes	Yes	Yes		Supply structure
[56]	Renewable energy system	Yes			MCDM	Cost, ren. Energy	Yes				
[57]	Hydrogen solar-storage		Yes		MILP	Cost	Yes		Yes		
[58]	Combined heating, cooling, power	Yes			no opt.		Yes	Yes	Yes	Yes	
[59]	Combined heating, cooling, power	Yes			LP	Cost	Yes	Yes	Yes	Yes	
[60]	Nearly-zero exergy airport	Yes			REMM	Exergy	Yes	Yes		Yes	Exergy
[61]	Building cooling heating and power	Yes			SQP	Op. Costs	Yes	Yes	Yes		
[62]	Review of different methods	Yes	Yes	Yes	no opt.		Yes	Yes			
[63]	Energy model existent airport	Yes	Yes		LP	Cost	Yes	Yes	Yes	Yes	
[43]	Ground support equipment		Yes		no opt.		Yes				Charact. El. Sys.
[64]	Power system	Yes			HOMER	Cost	Yes		Yes	Yes	
[65]	Energy hub	Yes	Yes	Yes	PSO	Cost, env. Impact	Yes	Yes	Yes	Yes	
[65]	Thermal energy system	Yes			MILP	Cost	Yes	Yes	Yes		

Different mathematical approaches are available for energy system optimisation: these can be, for example, linear, dynamic, mixed integer linear or agent-oriented programming, fuzzy logic or heuristic methods [66]. A variety of these are used in different airport energy system optimisation studies as shown in Table 3.1:

- The most commonly used optimisation method is linear programming (LP), which allows to find an optimal solution based on an objective function and a set of constraints, which are both defined as a linear function of the employed decision variables [67].
- Mixed-integer linear programming (MILP) is a specific type of LP, where both integer as well as non-integer variables are allowed [67].
- In sequence quadratic programming (SQP), multiple quadratic model optimisations of linearised constraints are performed after each other to find the optimal solution in an iterative progress [61].
- For particle swarm optimisation (PSO), a swarm of solutions is generated, wherein every solution moves towards an optimal solution throughout an iterative process based both on its own optimal solution as well as the optimal solution of the swarm until reaching a global optimum [68].
- Hybrid fuzzy-stochastic programming (HFSP) combines fuzzy programming, joint probabilistic constraint programming and Monte Carlo techniques and manages uncertainties by modelling them as fuzzy sets and as probability distributions, thus leading to improved performance [55]. However, large-scale problems are hard to solve using this technique.
- The method of Rational Exergy Management Model (REMM) is a novel method based on the exergy on the energy supplied and required and restrains the consumed primary energy as well as the emissions based on the match between supplied and required energy [60].
- Multiple Criteria Decision Making (MCDM) is a more systematic approach of approaching problem with a clearly defined decision-making process [56].

Different optimisation tools are available for energy system optimisation and were employed in the different studies. One example is the Hybrid Optimisation Model for Electric Renewable (HOMER), which was developed by the National Renewable Energy Laboratory in the United States and which allows to simulation many configurations of energy systems based on climate and technical component data [64]. Another option is the OSeMOSYS framework, which allows to model energy systems from village up to global scales in a modular structure also allowing the implementation of long-term dynamics such as changes in energy prices or demand [63].

Regarding the design variables, these are often the sizes of the different energy technologies employed. However, different more specific design variables might be employed to limit the number of design variables and thus reduce complexity of the optimisation problem. For instance, Kilkis and Kilkis [60] employed only three main design variables, being the co-generation engine capacity and peak power, the allocation of generated power supply and the mixing ratio between natural gas and biogas. This allowed to solve the optimisation problem using ”a simple search method” [60].

3.1. Buildings

Buildings are a frequent scope of analysis in literature. An overview of the studies optimising the building energy system is shown in Table 3.2, including both the demands and the technologies considered in those studies.

From Table 3.2, it can be seen that most studies focus on the heating, cooling and power supply of the airport buildings [41], [55], [59], [60]. Only a few studies focus solely on individual demands, for example, the electric power supply [56], [64], electric power supply combined with cooling [61] or fulfilling the thermal demand of an airport [69]. In addition to the building demands, a few studies are also considering the electricity demand of vehicles, which are either simple light-duty and maintenance vehicles [63], the ground service equipment or a possible additional load due to electric aircraft [65].

Jin and Li [55] found that their hybrid energy system combining technologies using natural gas and electricity was most sensitive to changes in the cooling demands, as cooling is required during nearly half of the year and as it relies on technologies consuming electricity which is more costly than the different types of fuel. Cardone et al. [59] furthermore found that the improvements from new energy systems get more important when the demand for heating and cooling is increasing. In general, for the energy demand of an airport, it is crucial to consider seasonal and daily variations, as the assumption of a fixed load, which is often made to reduce computational complexity, can lead to erroneous or inaccurate results [64]. It is also important to consider seasonal and daily variations in the energy sources,

Table 3.2: Demands considered and technologies employed in different airport optimisation studies considering the airport building energy demands

Airport and reference		15 airports [41]	Changsha [55]	none [56]	Malpensa [58] [59]	Schiphol [60]	Qingdao [61]	Turin [63]	Incheon [64]	Kansai [65]	Geneva [69]
Demands	Heating	Yes	Yes		Yes	Yes		Yes		Yes	Yes
	Cooling	Yes	Yes		Yes	Yes	Yes	Yes		Yes	Yes
	Power	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
	Mobility									Yes	
Electricity Generation	PV	Yes	Yes	Yes		Yes			Yes	Yes	Yes
	Wind	Yes		Yes					Yes	Yes	
	Geothermal power			Yes							
	Gas turbine	Yes	Yes		Yes		Yes			Yes	
	Steam turbine	Yes									
	Biodiesel generator			Yes							
	Thermoelectric generator									Yes	
	Internal comb. Engine	Yes									
Heating	Gas boiler	Yes	Yes		Yes			Yes		Yes	Yes
	Diesel boiler							Yes			
	Electric boiler/heater	Yes									Yes
	Heat boiler									Yes	
	Electric heat pump	Yes									
	Ground source heat pump		Yes			Yes					
Cooling	Absorption chiller	Yes	Yes		Yes	Yes	Yes				
	Compression chiller	Yes	Yes		Yes		Yes	Yes			Yes
Combined	Combined heating & cooling	Yes									
	Combined heating & power					Yes					
	HVAC	Yes									
Hydrogen	Methane reactor									Yes	
	Electrolyzer									Yes	
	Hydrogen-oxygen fuel cell									Yes	
Storage	Hot water storage	Yes	Yes			Yes					Yes
	Chilled water storage	Yes	Yes				Yes				
	Ice thermal energy storage	Yes				Yes					
	Electrochemical storage	Yes		Yes					Yes	Yes	
	Hydrogen storage tank									Yes	
Others	Desalination	Yes									

which influence the availability and costs of the energy generated from the different technologies employed.

Next to the demands, Table 3.2 displays the technologies employed in the related studies. Multiple different technology options are considered for electricity generation, heating and cooling, respectively. Many studies furthermore add the option of energy storage, which could be achieved using thermal (hot water, chilled water, ice), electrochemical and hydrogen storage systems. Hydrogen generation and usage are only modelled in one study, which also includes the demands of mobility and thus uses hydrogen as a renewable alternative for mobility applications [65]. Different to the energy generation and storage technologies, desalination is added as a possible water source alternative, which can be employed when the charges for buying the required volume of water are too expensive [41].

Overall, it can be seen that PV power is the most commonly suggested electricity generation method next to electricity coming from the grid. However, PV panels might be a risk for the pilot due to glare effects, which need to be carefully investigated before deciding on where PV panels can be placed at an airport [60]. Common alternatives for electricity generation are wind energy and gas turbines. For heating and cooling, gas boilers or ground source heat pumps and absorption or compression chillers are implemented most often.

Although the use of PV systems might be limited because of glare effects, they should not be dismissed entirely. Instead, careful consideration should be given to their placement, as they are highly appealing due to their often lower levelised cost of electricity compared to grid prices [41]. Wind energy can be a promising alternative to PV in achieving emission-free or nearly zero-exergy airports [60]. Wind energy can be generated both on-site and off-site from the airport.

In general, many studies observe the potential of combined technologies: these could, for example, be combustion engines for combined heating and power [41], combined heating, cooling and power units based on a combination of a gas turbine, boiler, absorption chiller and an auxiliary electric chiller [58] or combined cooling, heating and power systems based on a gas turbine and an absorption chiller [55]. The costs of these systems can be reduced through an optimal mix of fossil and alternative fuels [60]. As an emission-free alternative, ground-source heat pumps also show comparable performances [55]. Looking at energy storage, it was seen that thermal energy storage is the most attractive option due to their lower investment costs compared to electrochemical energy storage [41].

The different studies also show the importance of considering variations in the grid: Jin and Li [55] found that the share of electricity from the grid varied between 86.2% and 48% depending on the current electricity price. Thus, the electricity and natural gas prices (and of other resources) and their variations over the day are crucial for identifying the optimal strategy [61]. Zhang et al. [61] observed that economically, it is more attractive to use electrical chillers during the night and absorption chillers with gas turbines during the day, as the electricity price decreased in Qingdao in off-peak hours during the night. Cheap electricity bought during off-peak hours can further be used to store chilled water obtained from the absorption for periods with higher energy prices.

From most of the studies, it is observed that creating an optimised energy system allowed for a significant reduction in costs. This demonstrates that the economic performance of the system relies on a well-designed operation strategy [61]. In fact, Zhang et al. [61] observed a 24% operation cost reduction for summer days due to their optimised building cooling, heating and power system with integrated thermal storage. Thiem et al. [41] found that for an integrated energy system with electricity generated on-site, up to 61% of total costs can be saved compared to the case of only using energy from the grid. Also, Cardona et al. [59] found in 2006 that a combined heating, cooling and power plant re-powering in 2010 for Malpensa airport would be profitable with a payback period of only 3.2 years.

Cardona et al. [58] additionally observed that even a non-optimised combined heating, cooling and power plant already allowed to achieve energy intensity, cost and emissions reductions, the latter being approximately 16.7% compared to the non-combined conventional system. However, the most cost-effective is not always identical to the most energy-efficient energy system [61]. In fact, Cardone et al. [59] observed a profit decrease of 583000€/year to achieve a 2.01% increase in the primary energy saving index, which was required to fulfil the energy saving requirements set by the European Union (EU). Thus, aiming for slightly less than the optimal profit allowed for much better energy efficiency and environmental performance. As a general comment, it can, however, be noted that those optimisation results should be taken with caution, as these simulations have limitations and as assumptions were made, which may lead to a good but not exactly the optimal result [64].

Next to employing an accurate model, it is also important to consider governmental regulations when developing new energy systems. An example of this can be seen at Incheon International Airport in South Korea [64], where the government has a policy of ”eco-friendly airport operations and preparations for a green future”, requiring the large-scale deployment of renewable energy and of measures to increase energy efficiency of airports.

Several general conclusions and recommendations can be drawn from the previous studies. Firstly, several data sources are used when developing an energy system model. Relying on more recent sources enables more precise parameter estimations, leading to more accurate results [55]. Additionally, when possible, the model should be validated against real data, as was done by Prussi et al. [63]. Secondly, energy systems are rarely overhauled abruptly. Therefore, long-term road-maps are essential to plan an airport's energy transition properly [64]. These road-maps can include retrofitting renewable energy technologies into existing energy systems, as was explored by Belfiore [69]. Finally, economies of scale must be considered when designing larger energy systems, as they often demonstrate better economic performance than multiple smaller ones [64]. However, systems with strong economic performance also tend to have a higher risk of violating constraints [55], creating a trade-off between robustness and cost-effectiveness.

3.2. Operations

Two main pathways are identified for transitioning airport operations, particularly ground support equipment, to renewable energy sources: implementing a fully electric system or integrating hydrogen. Kirca et al. [43] focused on the first of the two, analysing the potential for the electrification of the ground support equipment across all categories. These included pushback vehicles, service vehicles (fuel, catering, etc.), loading vehicles (conveyor, passenger stairs, etc.) and power supply for the aircraft. The model determined the optimum between the number of ground support equipment vehicles required and the required recharging instances for varying battery capacities. It was found that the charging schedule plays a crucial role. For instance, charging during the day, in addition to nighttime, reduced the microgrid's peak load by 23% and shortened its duration by 28%. Overall, the electrification of the ground support equipment avoided 60% of the CO_2 emissions. In the future, it was recommended that options for vehicle-to-grid storage, better grid profiles, and electrification of a full airport be looked at.

In addition to a fully electric system, hydrogen can be used to fuel vehicles or added as a storage resource. The latter was investigated in two related studies by Zhao et al. [54], and Xiang et al. [57], where hydrogen storage and supply as electricity after conversion in a fuel cell was introduced next to the PV technologies, the electricity grid and batteries. Next to the vehicles, the APU of the aircraft was also considered. In the latter study, hydrogen was also used to power the APU [57]. Using renewable technologies and hydrogen allowed to reduce the total annual costs by 41.6% and the emissions by 67.29% [57]. Furthermore, even if the hydrogen technologies seemed to be expensive at first, they allowed to achieve lower cost and environmental impact in the long term when their investment paid off [57]. Together with PV technologies and battery storage systems, they also allow to compensate for less available electricity from the grid [54]. The most economical solution further improves when having a higher solar irradiance, a lower cost for hydrogen systems and increasing oxygen prizes, whereas it remains unchanged for varying prices of electricity from the grid, emissions from the grid and the carbon tax [57].

3.3. Overall Airport

Tian et al. [65] focused on optimising the entire energy system of the airport, trying to satisfy the building heating, cooling and power demands, light demands over the airport, the demands for ground support equipment and even the demands for possible future electric aircraft. As shown in Table 3.2 they employed various technologies for the energy system, ranging from electricity generation to regular boilers and hydrogen technologies. The authors concluded that the daily variation of demands could be beneficial as the periods with no demand correspond to periods with no sun and, thus, no electricity production from PV. However, the edge times (07:00-08:00 and 18:00-20:00) are critical because of the mismatch between demand and the limited availability of sunlight during those periods. Hence, wind and natural gas generators are interesting alternative resources for stabilizing the electricity supply during periods with less PV output. Combining electricity generation technologies from waste heat, gas turbines, and hydrogen fuel cells displayed how heat and electricity usage and generation can be interconnected. Finally, by including the charging needs of electric aircraft, it was observed that their demand represents a large part of the total load, requiring the use of grid electricity in addition to local electricity sources.

4 Energy Technologies Suitable for Airport Environment

In the previous section, an overview of different studies on optimising airport energy systems is given. In Table 3.2, the energy technologies employed in those studies are presented. A variety of technologies are observed in the optimised superstructures. Through the choice of innovative locally applicable technologies, the energy system can benefit from its environment, such as, for example, through the introduction of ocean energy in coastal regions [62].

Consequently, this section attempts to provide an outline of the technologies that could possibly be employed in an airport energy system. This will be done by giving an overview of the technologies for electricity generation in Section 4.1, for heating and cooling in Section 4.2 and for energy storage in Section 4.3. Their respective advantages and disadvantages will be outlined. Furthermore, possible technologies for the production of hydrogen and sustainable aviation fuel (SAF) are explored in Section 4.4 and 4.5.

4.1. Electricity Generation

Local electricity generation technologies can be used at the airport or on sites close to the airport and thus allow for the airport's self-sufficiency. They allow to avoid variable electricity grid availability and costs, as was seen previously in Section 3.1. The most commonly used renewable electricity technologies are PV and wind turbines, which, however, have limitations in the airport environment, as seen amongst others in the subsequent list. Smaller wind turbine technologies would thus, for example, be beneficial, as their possible placements are less restricted than for conventional wind turbines [70]. An alternative resource with underestimated potential [71] are, for example, micro-nuclear power plants, which are ideal for sites such as airports with high energy consumption and which require flexible and reliable energy supply [71]. Alternatively, fuel cells [72] and geothermal electricity generation [73] are flexible electricity sources which can supply the airport with electricity reliably. Finally, hydropower and ocean energy are two other possible sources of electricity which are reliable [74] or have synergies with solar or wind energy [75], but they require a river, mountains or an ocean nearby and are thus limited to the geographical constraints of the airport. The following list gives an overview of the advantages and disadvantages of all technologies.

PV

Advantages:

- Renewable [76]
- Large technological development and cost reductions over the past 20 years [76]
- Competitive levelised cost of electricity [76]
- Large surface areas available for PV at the airport [77]

Disadvantages:

- Long return on investment time [76]
- Rare and hazardous materials used [78]
- Currently often disposed at end-of-life [78]
- Glare effects might disturb pilots [79]
- Possible radar interference [77]
- Intermittent solar radiation [80]

Wind Turbines

Advantages:

- Renewable [81]
- Large areas available at airports [82]
- Significant technological progress over the past 20 years [81]
- Competitive with conventional electricity sources [83]

Disadvantages:

- High wind turbines physically interfere with airspace [82]
- The current trend towards longer blades [81]
- Cluttering effects and radio interference [82]
- Complex recycling of wind turbine blades due to carbon fibres [84]
- Intermittent wind energy [81]

Nuclear Micro-Reactors

Advantages:

- Emission-free [85]
- Large and underestimated economic potential [71]
- Flexible sources of energy [71]
- Ideal for high-intensity energy consumers such as airports and remote locations [71]
- Small footprint [86]
- Long life [86]
- Use passive cooling independent of electricity supply [85]

Disadvantages:

- Partly low TRL [86]
- Safety concerns for nuclear energy [85]
- Disposal and isolation of nuclear waster [85]
- Nuclear power abandoned in some countries [85]

Hydropower

Advantages:

- Renewable [87]
- Available when intermittent resources are unavailable [87]
- Reliable [74]
- Advanced technology [74]

Disadvantages:

- Negative impact on local environment [87]
- High investment costs [87]
- Possible effects of seasonality [87]
- Only possible to use with adequate geography [74]

Ocean Energy

Advantages:

- Renewable [88]
- Economies of scale expected to decrease costs [75]
- Possible synergies with offshore wind energy [75]

Disadvantages:

- Not far in development [88]
- Require proximity of the airport to the ocean
- Require a significant amount of materials [88]

Fuel Cells

Advantages:

- Can be used for combined heating [72]
- High electrical efficiencies compared to other combined technologies [72]
- Can quickly start running in case of varying demands in energy [72]

Disadvantages:

- Emissions depend on production of fuel used [72]
- Reliability of fuel cells can be an issue [89]

Geothermal Electricity

Advantages:

- Renewable [73]
- Available all around the year and the Earth [73]
- Competitive costs [73]
- Flexible [73]

Disadvantages:

- Electricity generation requires medium- to high-temperature geothermal sources [73]
- Possibly difficult process to obtain permit [73]
- Energy waste and environmental concerns can be problematic [90]
- Risk of induced seismicity [91]

4.2. Heating and Cooling

Next to electricity, the second main demand of the airport buildings is heating and cooling. The subsequent list presents commonly used technologies for building heating. First, the widespread technologies of fossil gas or oil boilers are presented, which, however, come with the drawback of a significant environmental impact [92]. Electric boilers [93] and biomass boilers [94] are presented as renewable alternatives for the same type of technology. Solar thermal collectors [95] or air-sourced heat pumps [96] are widespread technologies which could be used instead of boilers. Furthermore, geothermal heat pumps show very high efficiencies [97] and could therefore be an option, they are however currently less used than air-sourced heat pumps [97]. Finally, the combined cooling, heating and power production is a very promising option, which could be used with different resources [98].

Gas Boiler

Advantages:

- Widespread technology [92]
- Relatively cheap [99]

Disadvantages:

- High environmental impact [92]
- Ban on gas boilers announced in many countries [100]
- Natural gas prices are volatile and depend on extracting countries [101]

Oil Boiler

Advantages:

- Widespread technology [92]
- Relatively cheap [99]

Disadvantages:

- High environmental impact (50% higher than for gas boilers) [92]
- An on oil boilers announced in many countries [100]
- Oil price are volatile and depend on geopolitical conflicts [102]

Electric Boiler

Advantages:

- Renewable [93]
- Lower installation costs than heat pump [93]
- Boilers are widespread technology [93]

Disadvantages:

- Much lower efficiency than heat pumps, up to four times more energy for the same amount of heat [93]
- Shorter lifetime than heat pumps [93]

Biomass Boiler

Advantages:

- Renewable [94]
- Biomass is relatively cheap [94]
- Waste can be reused [94]

Disadvantages:

- The low energy density of biomass [94]
- Higher particulate emissions than natural gas or oil [94]
- Crops might be used, and thus, this technology could compete with food production [94]

Solar Thermal Collectors

Advantages:

- Renewable [95]
- Widespread technology [95]
- On-site heat production

Disadvantages:

- Large areas required for solar thermal collectors [95]
- High investment costs [95]

Air-Sourced Heat Pumps

Advantages:

- Renewable [96]
- Currently, the most widespread heat pump technology [97]

Disadvantages:

- COP is dependent on the environment and air temperature and thus highly variable [96]

Geothermal Heat Pump

Advantages:

- Renewable [96]
- High efficiencies [97]
- Underground temperature is relatively stable and thus only small COP variations [96]

Disadvantages:

- High costs for drilling and installation [97]
- Risk of induced seismicity [91]

Combined (Cooling), Heating and Power

Advantages:

- Renewable resources can be implemented [98]
- Allows the integration of different types of energy production efficiently by, for example, recovering waste heat from electricity production for heating [98]
- High overall efficiency [98]

Disadvantages:

- Environmental performance depends on the fuel used

Next to the heating technologies, the following list gives an overview of possible technologies for cooling. Absorption and compression chillers are two of the most common technologies used for cooling [103]. Compression chillers seem to be the better option for large-scale cooling applications [103]. A smaller alternative for active cooling is a packaged terminal air conditioner [104]. Night ventilation and wind towers are included as two passive cooling options, which could be combined with active cooling technologies to reduce their energy consumption [104].

Night Ventilation

Advantages:

- Passive cooling technology [104]
- Can be combined with active cooling [104] to reduce energy consumption

Disadvantages:

- Outside air can enter the building [104]
- The emissions from which can cause health problems [105]

Wind Tower

Advantages:

- Passive cooling technology [104]
- Simple technology with no moving parts [104]
- Wind towers could rotate to orient with respect to wind direction [106]
- Reduce energy consumption for cooling [106]

Disadvantages:

- Cooling performance depends on wind velocity and direction [104]

Packaged Terminal Air Conditioner

Advantages:

- Common active cooling technology for commercial buildings [104]
- Simple installation [104]
- Relatively small [104]

Disadvantages:

- High investment costs [104]
- Noise pollution/vibration [104]
- Only applicable for small or medium-sized spaces [107]

Absorption Chiller

Advantages:

- Can use various heat sources such as waste or solar heat [108]
- Flexible [108]
- No global warming contribution [104]

Disadvantages:

- Smaller efficiency compared to compression chiller [104]
- Less expensive and less maintenance required than compression chiller [103]

Compression Chiller

Advantages:

- Dominant over absorption chiller for small or medium cooling application [108]
- High energy efficiency [103]
- Compact [103]
- Better for high-capacity cooling [103] such as at airports

Disadvantages:

- Synthetic refrigerants used which have negative environmental impact [103]
- Noise pollution [103]

4.3. Energy Storage

Energy storage could significantly help to reduce the effect of intermittent renewable energy sources on the energy system [109]. Different forms of energy storage exist, which will be presented in ??. For short-term storage, flywheels are preferred, but they come with the drawback of very fast discharge rates [110]. Pumped hydro or compressed air, on the other side, show low discharge rates and are suitable for long-term storage but come with the drawback of low energy and power density [111]. Batteries and supercapacitors are a mature and not yet mature technology respectively to store electricity directly without pumping water or compressing hydrogen and thus have faster response times [111], but are more expensive than, for example, pumped hydropower [99].

Multiple options exist for hydrogen storage. First, hydrogen can be stored in a pressurised form, requiring a large volume [112]. The second option is cryogenic storage, allowing a high storage density but requiring a lot of energy [112]. Finally, metal hydride storage could be used by creating chemical bonds between hydrogen and the metal material, but this requires the use of expensive materials [112].

Three options are also presented for thermal storage. Sensible heat storage comes with low costs but also lower storage efficiencies [113]. Latent heat and chemical thermal storage cost more, but also have higher storage efficiencies, the latter however being a complex technology still in development [113].

Flywheel

Advantages:

- Perfect for standby power [110]
- High power levels [110]
- High energy efficiency [111]
- No depth-of-discharge effects [110]
- High cycle life [110]
- Can be used for frequency regulation [114]
- Can help with the intermittency of renewable energy [114]

Disadvantages:

- High self-discharge rates (20% per hour) [110]
- Not suitable for long-term storage [110]
- High costs [110]

Pumped Hydropower

Advantages:

- Low self-discharge rate [111]
- See Hydropower in Section 4.1

Disadvantages:

- Low energy and power density [111]
- See Hydropower in Section 4.1

Compressed Air

Advantages:

- Low self-discharge rates [110]
- Flexible storage durations [110]
- Can be stored efficiently and safely underground [110]

Disadvantages:

- Still in development [110]
- Requires caverns suitable for storage [110]
- Low energy and power density [111]

Battery

Advantages:

- Mature technology [111]
- High energy efficiency [111]
- High energy and power density [111]
- Fast response time [111]

Disadvantages:

- Low lifetime in terms of cycles and years [111]
- Use of harmful materials and chemicals [115]
- Battery waste has a significant environmental impact [115]

Supercapacitor

Advantages:

- High power density [111]
- High energy efficiency [111]
- Fast response time [111]
- Many cycles possible [111]

Disadvantages:

- Low energy density [111]
- High self-discharge [111]
- Not yet mature technology [111]
- Expensive [116]
- Packing difficult [116]

Pressurised Hydrogen

Advantages:

- Can be stored in pressure vessels or underground [112]
- Low operating costs [112]

Disadvantages:

- Large volume required for storage [112]
- Leakage can be an issue [112]
- High investment costs [112]
- Expensive high-pressure tanks (700 bar) not viable [117]

Cryogenic Hydrogen

Advantages:

- The high density of storage [112]

Disadvantages:

- Utilises a lot of energy [112]
- Expensive storage vessels [112]
- Expensive liquefaction consumes a lot of energy [117]
- Boil-off must be analysed [117]

Metal Hydrides Hydrogen

Advantages:

- Multiple different materials can be used [112]
- Some metal hydrides employ largely available materials which are easily recyclable [118]

Disadvantages:

- Issues such as managing the heater and expensive materials [112]
- Actual hydrogen storage capacity lower than values from theory [118]

Sensible Heat

Advantages:

- Low costs, as normally only composed of tank and charging/discharging equipment [113]
- Simple system [113]
- Underground storage possible [113]
- Commercial [113]

Disadvantages:

- Medium storage efficiencies of 50-90% [113]
- Capacity limited by storage medium specific heat [113]
- Large space requirement [110]

Latent Heat/Phase-Change

Advantages:

- High capacities [113]
- High storage efficiencies of 75-90% [113]
- Discharging temperature can be set [113]

Disadvantages:

- High costs due to required technology for heat transfer [113]
- Complex technology [113]
- In development [113]

Chemical Thermal Storage

Advantages:

- High storage efficiencies of 75-100% [113]

Disadvantages:

- High costs due to required technology for heat transfer [113]
- Expensive materials, containers and auxiliary equipment required [113]
- Complex technology [113]
- Stability can be an issue [113]
- In development [113]

4.4. Production of Hydrogen

Hydrogen technologies are increasingly used across the world, playing a key role in the energy transition, especially because of hydrogen's energy storage potential [119]. Consequently, there is an increasing demand for green hydrogen. Besides energy storage applications, hydrogen could be used in vehicles operating at the airport and as aviation fuel in the future [62]. Currently, hydrogen is mostly produced using fossil resources such as natural gas through steam methane reforming (SMR) [120]. However, this process has high direct emissions of 9.35kgCO_2eq per kilogram of hydrogen produced [120].

It is possible to produce green hydrogen using water or biomass as a primary resource [121]. In the first case, water electrolysis using alkaline electrolysers is the most used technology, presenting efficiencies between 62-82%[1] [122]. Other electrolysers include polymer electrolyte membranes (PEM) (67-82% efficiency[1] [122]), anion exchange membranes, and solid oxide electrolysers (SOEC) [123]. Although presenting promising efficiencies (<110%[1] [122]), SOECs operate at temperatures of 700-1000°C [122] and are still too expensive, requiring further developments to reach a commercial state [123]. Some advancements have also been made in thermochemical water splitting, photoelectrolysis and photolysis to produce hydrogen with water and heat or sunlight, respectively, but are also still far from reaching technological maturity [122].

From biomass, hydrogen can be produced through biogasification or pyrolysis, with efficiencies of 30-60% and 35-50%, respectively [121]. From the latter two processes, CO and CH_4 are obtained. Through processing, these two products allow a rise in the production of hydrogen in SMR and water-gas shift reactions [121]. Using biogasification, a reduction of 78.1% of CO2 emissions is achieved compared with conventional SMR [120]. Furthermore, those emissions are considered carbon-neutral [121]. Developments have also been made for biomass hydrothermal liquefaction [124], allowing hydrogen production at similar efficiencies (85-90%) to SMR [121]. Other technologies from biomass, such as dark fermentation or photofermentation, are still far from reaching technological maturity [122].

4.5. Production of Sustainable Aviation Fuels

In the previous subsection, the option of hydrogen as an aviation fuel was mentioned. However, the most probable future green aviation fuel will be SAF. In 2015, the International Air Transport Association published the first edition of its SAF roadmap [125]. At the same time, several airlines signed agreements with SAF suppliers [125] to have sufficient resources as they expected SAF to become increasingly important in the future. In fact, in 2023 in the EU the European Council adopted a law which requires 2% of SAF in aviation fuel by 2025, 6% by 2030 and 70% by 2050 [126], showcasing the importance of the development and large-scale deployment of production technologies for SAF, possibly also at airports, to achieve these ambitious goals.

There are multiple paths for the production of SAF: In general, they can be classified as biofuels, which are produced from renewable materials on a carbon basis, or as synthetic fuels, which are typically produced from syngas [127]. For both of them, multiple pathways are currently in development or even approved [127]. For biofuels, these are, for example [127]:

[1] "Voltage efficiency (%) based on HHV of hydrogen (may be greater than 100%)" [122]

- Fischer-Tropsch: Syngas is produced from gasification at high temperatures, which is then converted in a catalyzed thermochemical reaction to liquid and gaseous hydrocarbons. Final refinement and distillation allows to obtain aviation fuel.
- Hydroprocessed Esters and Fatty Acids: Biogenic material is purified, the resulting oil is deoxygenated, subsequently cracking and isomerisation of the hydrocarbons takes place, before the aviation fuel is obtained through distillation and separation.
- Hydroprocessed Fermented Sugars: Sugar is transformed into hydrocarbons using fermentation, which is then hydroprocessed in an alkane. Aviation fuel is finally obtained from distillation.

To obtain synthetic fuels, there are two main options [127]:

- Power-to-Liquids: Hydrogen obtained from the electrolysis of water is combined with carbon dioxide. The mixture can subsequently be synthesised and synthetic fuel is obtained using upgrading of the synthesised mixture.
- Sun-to-Liquids: Concentrated solar radiation allows the synthesis of a mixture of water and carbon dioxide. Synthetic fuel can subsequently be obtained again by upgrading the obtained synthesised mixture.

Cabrera and de Sousa [127] observed, that synthetic fuels at the moment still require further improvements in technology, for example, for co-electrolysis, to reduce costs to a competitive level to biofuels. However, in the future, they are expected to be economically more attractive than biofuels. Still, according to them, both biofuel and synthetic fuel pathways will be important to reach a sufficient production level for achieving the goals set for the use of SAF.

5 Research Gap

It is observed from the literature review that most studies on airport energy systems are either centred on studying the terminal building or on the fuel and electricity supply to ground equipment or other vehicles at the airport. A similar observation was made by Zhou [62], who found that most studies were centred on determining the airport energy demand by designing HVAC systems or energy systems for electric vehicles at an airport. Only a few studies have looked at the entire airport, including buildings, ground support equipment, and possibly other vehicles and aircraft demands. Furthermore, previous studies often looked at the optimisation of a very specific combination of energy technologies, for example, by focusing on renewable electricity generation sources with a battery or at combined heating, cooling and power units. An optimisation with multiple possible technologies, where the optimisation selects the optimal ones, was done less frequently. This approach of using a superstructure is often employed in process integration [128] for obtaining multiple different configurations of technologies, with different configurations being optimal for different external conditions.

In consequence, the two observations just mentioned lead to the research gap, which is the basis of this study. The research gap consists of the combination of the following six points:

- Optimisation of a fully integrated airport energy system, including the airport buildings, the ground support equipment, other vehicles and possibly aircraft demands.
- Build-up of an extensive superstructure for the airport, which includes all possible technologies that can be used at an airport.
- Analysis of the robustness of the different combinations of energy technologies under varying operational circumstances.
- Sensitivity analysis of the resulting airport energy system on different technological or environmental parameters.
- Inspection of the effect of connecting the airport's energy system to its environment, such as close-by cities or industries.
- Examination of a possible production of SAF or hydrogen on or close to the airport.

In summary, the identified research gap lies in an all-encompassing approach to determining optimal energy systems for airports of varying sizes and environmental conditions. This will allow to assess which technologies are most robust under varying circumstances, to identify what technological or economical improvements are needed for the technologies to become attractive in the future, and to evaluate the feasibility of a fully-renewable and self-sufficient energy system for an airport. Overall, this study can serve as an advisory guide in the design of future energy systems, with the optimal system providing a benchmark for airport energy systems. Additionally, it will propose a range of metrics to quantify the resulting configuration, ensuring comparability for future research.

6

Research Plan

After finalisation of the literature review, the research plan is developed. It is constructed with the goal of answering the research question, as is outlined in Section 6.1. From the list of research sub-questions, the organisation of the thesis is set up in Section 6.2.

6.1. Research Question

The research question follows from the research gap explained in Chapter 5. It is defined as follows.

> *„To what extent could European airports, such as Schiphol airport, benefit from the concept of renewable energy hubs in reducing their sustainability impact and increasing their energy supply self-sufficiency while fulfilling the varying energy demand profile from airport operations and infrastructure?"*

Several sub-questions can be derived from the research question, which are guiding the research. They can all be further divided into a set of tasks, which allows to answer the respective sub-question. The eight sub-questions defined for this thesis and their tasks are as follows:

1. **What are the most important parameters influencing the overall energy demand of an international airport?**

   1.1 Analyse airport energy demand division

   1.2 Identify and quantify main airport energy demands

   1.3 Identify factors influencing airport energy demand

   1.4 Identify the time-wise distribution of energy demands and influencing factors

   1.5 Define the relation between airport energy demands and factors influencing the demand

   1.6 Create a model calculating energy demands based on pre-defined factors for different airports

2. **Which technologies are suitable for providing energy for an airport and how can these technologies be combined in an energy system?**

   2.1 Identify possible energy technologies

   2.2 Choose realistic and promising technologies for implementation in a superstructure

   2.3 Implement models for energy technologies in OSMOSE (with associated costs and emissions)

   2.4 Verify and validate implementation of energy technologies

   2.5 Build energy system superstructure

   2.6 Verify and validate energy system superstructure

3. **Is the introduction of energy storage technologies beneficial for levelling the intermittency of electricity supply as well as seasonal energy supply variations?**

3.1 Identify possible energy storage technologies
3.2 Choose most suitable energy storage technologies
3.3 Implement models for energy storage in OSMOSE (with associated costs and emissions)
3.4 Verify and validate implementation of energy storage technologies
3.5 Confirm correct time-variations of energy demands and technologies
3.6 Determine new optimal energy system with storage technologies
3.7 Analyse effect of added storage options on results

4. **Is it possible for an airport to have a fully self-sufficient energy system or what energy resources need to be imported in all cases?**

   4.1 Optimize fully self-sufficient energy system with resources at the airport
   4.2 Determine (if needed) what amount of resources (for example electricity from the grid) needs to be imported
   4.3 Propose (if required) options for local energy production near to the airport for supplying the required demands

5. **Is it an economically competitive option for an airport to fully rely on renewable energy technologies and resources for its full energy system?**

   5.1 Optimize fully-renewable energy system with developed superstructure
   5.2 Optimize energy system also including non-renewable energy technologies
   5.3 Compare costs and emissions of both energy system options
   5.4 With research hypotheses 4, assess whether zero-emissions energy system is possible
   5.5 With research hypotheses 7, look at what changes in costs would make renewable energy system attractive
   5.6 Analyse and discuss different types of sustainability

6. **Which combination of energy technologies is most robust to different airport environments and to changes in the airport operational circumstances?**

   6.1 Based on the energy model defined, determine energy demand for multiple airports of different sizes and in different environments
   6.2 Identify technologies which can(not) be used in different environments or the varying efficiencies
   6.3 Determine optimal energy system for the defined airports
   6.4 Analyse changes in the chosen technologies in different environments

7. **How sensitive is the optimal energy system to variations in the energy technology characteristics or costs?**

   7.1 Determine most significant possible variations in terms of costs or technology characteristics for implemented technologies
   7.2 Run sensitivity analysis on identified characteristics
   7.3 Analyse impact of variations
   7.4 Determine what cost reductions, efficiency improvements, etc. are needed for technologies to be chosen

8. **Is it an option to produce SAF on the airport and does it have an advantage compared to importing it from outside the airport's energy system?**

   8.1 Identify possible SAF production technologies
   8.2 Choose most suitable SAF production technologies

8.3 Implement models for SAF production in OSMOSE (with associated costs and emissions)
8.4 Verify and validate implementation of SAF production technologies
8.5 Determine demand of SAF on airports
8.6 Optimize energy system with additional SAF demand and production technologies
8.7 Determine energy quantities that would need to be imported or additional energy production site sizes that would be required for supplying energy demands for SAF

6.2. Organisation

The research sub-questions and their related tasks can be used for defining the thesis schedule, for which a Gantt chart is developed, as can be seen in Figure 6.1. In the first six weeks, the literature was reviewed, and this research plan was developed. In the subsequent seven weeks until the midterm review, a first working demand model and energy system optimisation framework is constructed and verified. Subsequently, the next 14 weeks until the greenlight review are used for extending the base model and producing results. Finally, during the last five weeks, the thesis is submitted, and the defence is prepared.

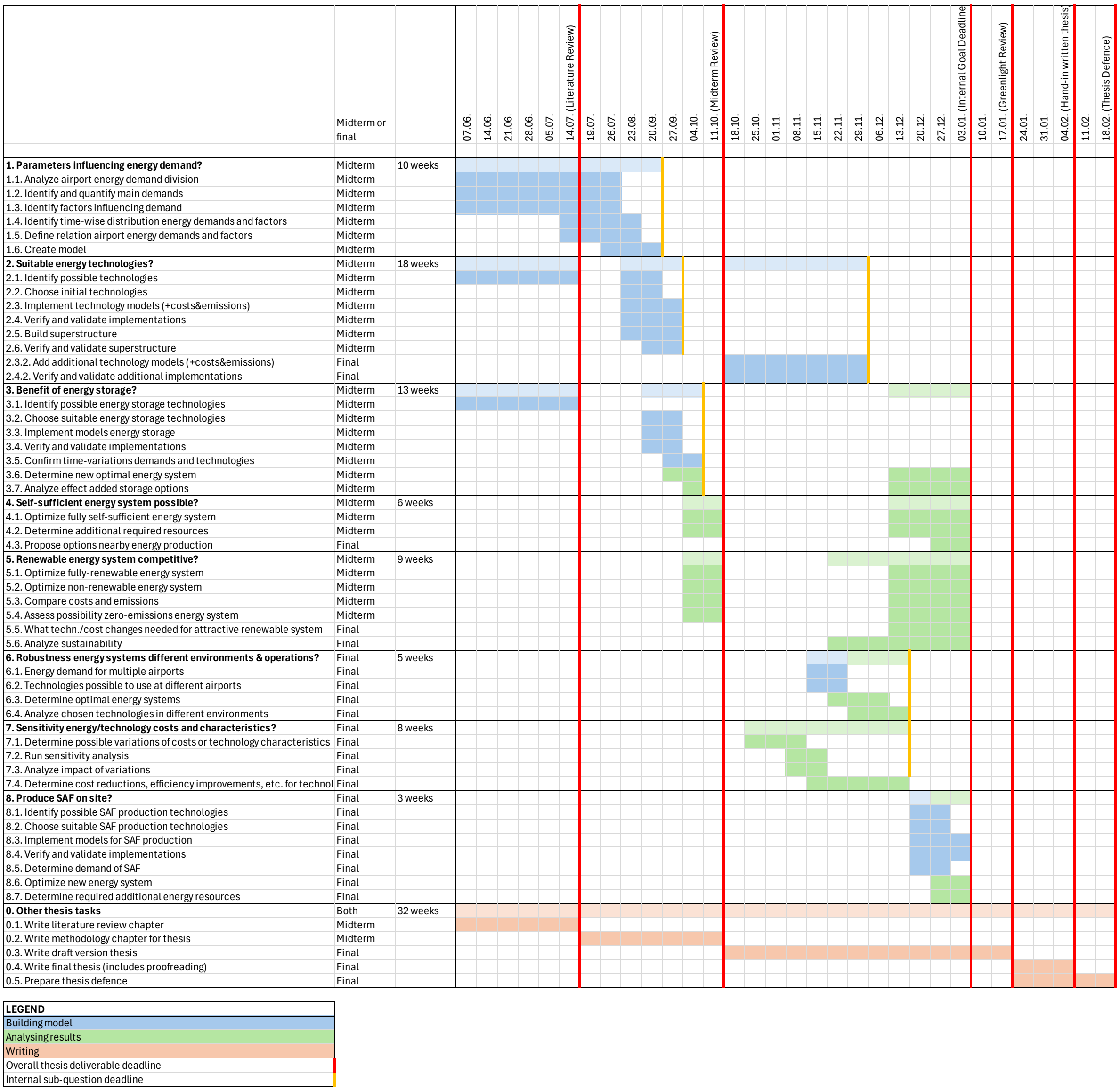


Figure 6.1: Gantt chart outlining Master's thesis organisation

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