TULIPS

Demonstrating lower polluting solutions for sustainable airports across Europe

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Concept designs of a smart energy hub at the airports for various scenarios

Description of methodology and results of scenario studies for the development of smart energy hub system concepts

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Abstract

This deliverable is a joint product by four airports with strong commitments to the climate goals and sustainable operation: Schiphol Airport working together with TNO as a knowledge partner, Torino Airport with SAGAT working with POLITO as a knowledge partner, Stavanger Airport with AVINOR working with SINTEF as a knowledge partner and and Larnaca Airport operated by HERMES Airports working together with EGIS as a knowledge partner.

The deliverable has a joint introductory chapter. In the following chapters, each airport provides a description of the airport, the methodology, the scenarios and solution pathways, the modelling results and the smart airport energy hub solutions. In the final chapter, joint conclusion are given.

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1 Executive Summary

Structure of this report

This deliverable is a joint product by four airports with strong commitments to the climate goals and sustainable operation: Schiphol Airport working together with TNO as a knowledge partner, Torino Airport with SAGAT working with POLITO as a knowledge partner, Stavanger Airport with AVINOR working with SINTEF as a knowledge partner and Larnaca Airport with HERMES working together with EGIS as a knowledge partner.

Chapter 1 is a joint introductory chapter. Chapters 2 to 5 are airport specific. In these chapters the methodology, the scenarios and solution pathways, the modelling results and the smart airport energy hub solutions are described for Schiphol Airport, Torino Airport, Stavanger Airport and Larnaca Airport respectively. The eight partners worked together in defining scenarios, modelling future developments and sustainable strategies, exchanging ideas and results and drafting pathways to zero emissions for the Airports involved. In this process, the Airports identified differences, commonalities and key elements of the future sustainable airport energy hub, which are listed in Chapter 6.

The transition of airports from traditional fossil-based energy sources to more sustainable energy solutions implies the transformation of all energy demanding units such as buildings, vehicles and airside supporting equipment. This transformation will inevitably affect the energy demand requiring a modification on the existing energy grid also considering that intermittent renewable energy sources will be more and more present inside airports. The creation of a smart energy hub enables the airport to efficiently utilize renewable energy sources produced on site and coming from the external grid and to optimise the infrastructure through load-shifting, sector-coupling and storage. This system should encompass all generation assets, infrastructure and energy needs such as electricity, heat and cold, hydrogen, biogas and other fuels.

<u>**Differences between airports**</u>

The four different airports analysed in this study differ in the context in which they operate. This imposes boundary constraints and enables or disables the adoption of specific technological pathways. In the following paragraphs the main factors affecting the technological choices are highlighted.

Geographical context. The latitude at which the airport is located affects significantly first of all the composition of the primary energy demand of the airport. As easily predictable, for northern airports' the weight of heating is more relevant if compare to southern regions, at the same time the cooling demand has a behaviour that is opposite. Since cooling demand synchronizes quite well with solar PV production but heat demand during winter periods does not, the airports specific energy need has a strong impact on the potential of certain technological solutions. Consequently this implies an easier access to electrification enablers for southern airports and a need of a wider range of options needed for airports with a significant heating demand.

National energy context. The availability of renewable resources can differ largely between the regions where the different airports operate in. In southern regions the PV plants are a more viable option both for on-site production (thanks to the high amount of equivalent hours) and for the purchase of green electricity from the grid, for northern airports a wider range of choices is present in particular thanks to the larger availability of wind plants and in some cases to the presence of larger amounts of biomass resources (both solid and through transformation in biomethane).

Size of the airport. The composition and scale of airport operations are crucial to the design of a smart energy hub. The presence of a large share of short haul flights combined with the possibility to operate smaller commercial aircrafts in northern regions implies the concrete possibility of having in the short term a large amount electric flights, thus implicating the need to supply and manage larger amounts of electricity at high power rates. For other airports the electrification of flights could be slower and less impacting, while at the same time the demand of hydrogen over time could be a variable to be taken into account.

The size of the airport also affects differently the operations, the type and amount of energy needed to meet decarbonisation targets: larger airports encounter difficulties in electrifying entirely GSE activities and need a wider range of options, while for smaller regional airports thank to a more compact geometry of the terminal the electrification of ground operations could be easier to be achieved.

Commonalities between airports

Although the smart energy concept introduced in the four studies differ in scope, all successfully employ smart grid strategies to meet energy demand and supply. Some common strategies have been identified and summarised below.

Energy efficiency. The reduction of primary energy supply is a cornerstone to achieve net zero targets and optimise the use of energy inside complex energy systems as airports are. Even if the increasing of energy efficiency is a pathway that has been followed by all the airports through the last years, there is still room for improvement and optimisation of the energy demand thus reducing the impact of the increasing demand of energy related to the transformations needed. At the same time reduction of primary energy demand releases part of the power used on existing electrical cabinets, reducing the need of new installations.

Electrification. From the analysis conducted, electrification of the energy demand is considered one of the most effective and resilient pathways to reach the net zero target. This can be developed both on the heating demand when lower grade renewable sources are not available and on airside operations with the effect of reducing the demand of fossil fuels and increasing the electricity demand accordingly. This phenomenon is already taking place at a faster rate than expected, but is currently slowed down by limitations of the available grid capacity from DSO/TSO's (congestion) at most airports involved. The future airport smart energy hub is expected to be complex and demanding to manage. Airports expect that to do this properly each airport needs to have the full ownership of the airport grid infrastructure.

On site production and storage. All airports introduce electricity generation on site, mostly in the form of solar PV: this is considered as a feasible way to decarbonise and at the same time to reduce grid dependency. In order to match the internal demand with the production and reduce as much as possible the export of energy exported to the external grid, all airports will consider different storage solutions. Other actions in this direction regard load shifting and peak shavings at cabinet level in order to match demand and renewable electricity production and to reduce congestions on the internal distribution grid. Another possibility proposed is related to smart charging devices that can enable airports to shift demand to periods of high renewable electricity production or alleviate infrastructural requirements.

Diversification of energy resources. A complex problem has to be faced with different solutions concurring to achieve the common goal of decarbonisation: diversification of energy streams (as for example hydrogen or biomass) can decrease infrastructural limitations even if at the same time can increase the airports dependency on external partners.

The regional energy infrastructure is often the limiting factor for the rate at which the transition of the airport is possible. Hydrogen, as a particular instance of external energy supply, will require the establishment of a dedicated infrastructure connecting the airport to hydrogen producers. The volume of hydrogen required by the airport for power generation purposes alone would likely be too small to justify significant investments in transport infrastructures over long distances. For a transition to a hydrogen infrastructure a concerted effort of the airport with local stakeholders towards the realization of a local hydrogen economy would be needed. Based on the studies, the deployment of H2 is not expected before 2030, potentially in the '40s.

Strategic cornerstones in the development towards Airports as a Smart Energy hub

The following cornerstones of the development towards a smart and sustainable airport energy hub were identified:

Increased self-sufficiency. Independently on the chosen technological pathway, a radical shift of the airport from the current *energy consumer* to *energy "prosumer"* role is expected and should be a pivotal part of the Airport energy strategy. This will allow to increase the resiliency of the energy system and at the same time to reduce the local based emissions.

Diversification of resources and sector coupling. Another constant of each strategy investigated lies in the increased complexity of the energy system. Under the current configuration of the airport, different energy sectors are compartmentalised and associated with specific energy carriers. The transformation required implies the creation of a sustainable, integrated energy system. The right energy mix will include: deployment of sustainable resources, energy storage systems to match supply and demand, smart charging and discharging facilities with H_2 as possible back-up system, for large scale vehicles.

Deployment of new technologies requires **long-term strategic approach**. New safety requirements (from an operational and permit standpoint) and risk based analysis need to be considered. Critical success factors like energy markets (size), geographic aspects, supply chain factors, workforce (availability of workforce with critical skills) need to be included, a human capital agenda is needed. The choice between on-site generation and market-based solutions needs strategic planning. Managing and operation of the local grid can be very demanding, especially when electric planes are introduced. To support the long-term strategy, dynamic modelling of energy needs can be useful, as it helps identifying the correct energy demand, how improved energy efficiency can impact the energy requirements, where and how electricity demand can be met by PV plants, and when and how much battery capacity is needed. These models can guide the decision making.

Need for external green energy supplies. Even if increasing the self-sufficiency of the airport s is one of the milestones of all energy strategies adopted, the analysis revealed that the realisation of an energetically autarchic system would be hard to achieve from an economic perspective. External supplies of green gases, either biomethane or hydrogen, and decarbonisation of the regional electricity grid represent a fundamental enabler of the energy transition of the airport.

2 Introduction

2.1 The TULIPS project

In 2019 the European Commission launched the European Green Deal strategy to overcome climate change challenges [1]. Complementary to this the Sustainable and Smart Mobility Strategy was published in December 2020. Greening transport is one of the key objectives of the Green Deal. Transport accounts for 25% of the EU's greenhouse gas (GHG) emissions [2]. The objective of the Green Deal is to reduce the GHG emissions of transport by 90% by 2050.

In this context, airports will play a major role in boosting the use of cleaner technologies, green energy carriers and smart logistics concepts in air transport, ground operations and road transport to and from Schiphol, both for passengers and freight, with the aim to reduce GHG emissions. The TULIPS consortium, formed by 29 partners across Europe and supported by an external advisory board, will develop innovations that facilitate the transition to low-carbon mobility and enhance sustainability at airports for the next four years. The goal is to accelerate the implementation of innovative and sustainable technologies towards lower emissions at airports, aiming to zero-emissions and zero-waste airports by 2030 and climate neutral aviation by 2050

2.2 Airports as Smart Energy Hubs

A Smart Energy Hub is a location where different functionalities of an energy system, such as production, storage and consumption, and different carriers of energy, such as liquid and gaseous fuels and electricity, are combined to achieve cost-effective, efficient and flexible means of supply of energy and energy related services in a highly integrated manner. When the system must deal with a certain degree of volatility in supply or demand, for example because of a dependency on weather conditions or human behaviour, a smart control system can assist in improved operations of the system, which can lead to a more efficient design and operations of the system on many fronts.

Airports are locations where many different activities are concentrated on one site. While the primary function (and business model) of an airport is to facilitate air travel of passengers and cargo, many buildings can be found on an airport premise. This includes both buildings required for the core process, such as terminals and piers, maintenance hangars, freight handling buildings, catering and others, as well as buildings used for secondary activity, such as offices, hotels, bars and restaurants. All in all, the built environment is well represented at an airport.

Additionally, a lot of mobility is taking place on and around the airport. On landside, trucks and lorries are driving on and off to pick-up and drop-off air cargo and supplies for the buildings. Cars, buses and taxis drive on and off to transport passengers, crew, airport staff and office employees.

On airside, vehicles are used to push around aircraft, to transport luggage, supplies, fuels and people to and from the aircraft and to supply electricity, conditioned air to the aircraft.

Today, many of these activities are fuelled by fossil energy carriers like diesel, petrol, kerosine and natural gas, resulting in significant emissions of carbon dioxide, nitrogen and particular matter. As each of these sectors have their individual challenges in their transition towards clean energy, airports are faced with the combination of these challenges.

But there are also opportunities. Airports require a lot of surface area, and typically have a lot of land available which can be used for development of large assets. Just think of the large-scale development of solar power on parking lots, roofs of utility buildings and open fields. Utility-sized facilities can be considered for (co)generation of electricity, heat and cooling and large-scale storage of energy. The airport may also be owner of the local energy infrastructure, which gives it a responsibility to provide energy to the local parties, but also gives the airport the position to develop the infrastructure in coordination with all other developments within the local energy transition. Finally, the airport operator is almost always connected to each stakeholder active on its site: ground operators, airlines, tenants, (..), providing the airport with a central position to organize and orchestrate the energy transition on its site: in many cases a must for a successful energy transition, and especially when trying to realize a Smart Energy Hub.

The extend to which the wide range of activities on an airport should be included in the Smart Energy Hub is not predetermined. For some cases, this may mean that every single energy consuming asset is in some way connected, for other cases it may be better to include only a subset of activities. What matters is that in due time airports set and achieve their climate goals and have a positive impact on the local and global transition towards clean energy and circularity. The concept of an airport as a Smart Energy Hub concept should help achieve this goal, in whatever way it can.

2.3 Key parameters airports

The different airports considered in this study strongly differ in size and the context where the operate. **Error! Reference source not found.** gives an overview of the characteristic parameters of each airport in terms of air transport related parameters, real estate, energy use and associated CO_2 emission.

Table 1: Airport key figures. Numbers refer to 2019.

	Indicator	Airport			
2019		**Schiphol**	**Torino**	**Stavanger**	**Larnaca**
	Passenger movements (PAX, x 1000) [#/annum]	80'521[1]	3'952	4'310	8'229
	Cargo (x 1,000 tonnes)	1'570 [2]	4.95		29.26
	Aircraft movements (landing and take-off) [#/annum] (air transport movements)	554'947 [3]	43'292	75'207	66'432
	Total gross floor area real estate [m2]	673'066 [4]	173'000	60'900	98'000
	Final energy demand [GWh/a]	250.7	22.7	18.092	24.73
	Total GHG emission [ton CO2 eq] (*Scope 1 and 2 – location-based)*	119'180[5]	6'590	516[6]	15'207

A comprehensive description of each Airport is given in Annex A.

As the airports differ in context, the scenarios studied and interventions considered are different. An overview is given in Table 2.2 for the scenarios and Table 2.3 for the interventions.

[1] Schiphol Group: Amsterdam Airport Schiphol, Rotterdam The Hague Airport and Eindhoven Airport
[2] Schiphol Group: Amsterdam Airport Schiphol
[3] Schiphol Group: Amsterdam Airport Schiphol, Rotterdam The Hague Airport and Eindhoven Airport
[4] Commercial real estate at Amsterdam Airport Schiphol. Total m2 at Amsterdam Airport Schiphol is more than 1'100'000m2
[5] Schiphol Group: Amsterdam Airport Schiphol
[6] Stavanger: Low CO2 emissions (Scope 1+2) due to very high share of hydropower in the domestic electricity generation mix and use of biomass for space heating.

Table 2 This table shows the different uncertainties that were considered in the scenarios studies as indicated by each airport team. ✓ means included , Identified as relevant uncertainty

	Airport: Schiphol	Torino	Stavanger	Larnaca
Developments in airport business				
Passengers processed at airport	(✓)	✓		✓
Cargo processed at airport	(✓)			
Flight movements at airport	✓	✓	✓	
Government mandated cap on flights	✓			
Building stock on airport premise	✓			
Developments in the energy sector				
Development of energy prices	✓	✓	✓	
Availability of electricity grid capacity	✓		✓	
Availability of importable biomethane		✓		
Availability of importable hydrogen gas	✓			
Developments in energy technology				
Renewable energy technologies	✓	✓	✓	✓
Electrolyser and fuel cell technology	(✓)	✓		
Energy storage technologies	✓	✓	✓	
Developments in transport technologies				
(Indirect) electrification of aircraft	(✓)		✓	
Electrification of vehicles	✓			✓
Electric and hydrogen-fuelled ground support equipment	✓			

Developments in airport climate				
Developments in outdoor temperature and solar irradiance				✓

Table 3 This table indicates the possible interventions considered in this scenario study as indicated by each airport team. Identified as possible intervention

	Airport			
	Schiphol	Torino	Stavanger	Larnaca
Deployment of renewable energy technologies				
Solar PV	✓	✓	✓	✓
Wind power (offshore/onshore)	✓		✓	
Hydrogen (import/onsite production)	✓	✓		
Biogas/biomethane		✓	✓	
Waste heat	✓			
Deployment of charging infrastructure				
For passenger EVs	(✓)		✓	
For buses	(✓)		✓	
For aircraft	(✓)		✓	
For ground support equipment	✓			
Deployment of energy storage				
Electricity storage systems	✓	✓	✓	
Hydrogen storage systems	(✓)	✓		
Heat storage systems	✓			
Implementing energy management (tactics)				
Smart grid energy management system	✓		✓	✓
Load shedding	✓		✓	
Smart charging/Vehicle to grid	✓			
Local energy market	✓		✓	

Improvement of building energy efficiency

Solar protection and insulation				
Improve operational				

3 Amsterdam Airport Schiphol – scenario study and system design concepts

3.1 Methodology

In this section, the methodological framework and applied models are presented. In this study, the solution space method was used to perform a scenario analysis for different technological pathways.

3.1.1 Methodological framework used for the scenario analysis

The transition towards a sustainable airport calls for changes in energy system of the airport. This transition introduces renewable energy generation and a shift towards greener transport options both airside as well as landside. Airports are complex infrastructures that have intertwined dependencies of various stakeholders. Thus, airport operators will need to make robust decisions under these high degrees of uncertainty.

The solution space methodology is a structured approach to tackle complex decision-making in which one or multiple stakeholders need to make individual or shared decisions while dealing with external uncertainties. The solution space methodology can be applied on decision problems where there are a large number of possible technological pathways and external uncertainties.

The solution space as shown in Figure 1Figure 1 Schematic representation of the Solution Space methodology is defined by matching the scenarios and development concepts. Both likely and less likely matches may emerge that, together, represent the complete solution space. Main objective of the methodology is to understand the 'Solution Space' and to demonstrate that a certain development concept is robust i.e. is feasible in most scenarios. The 'Solution Space' helps prioritizing resources and efforts that will be required to decide on the selection of an optimum development concept.

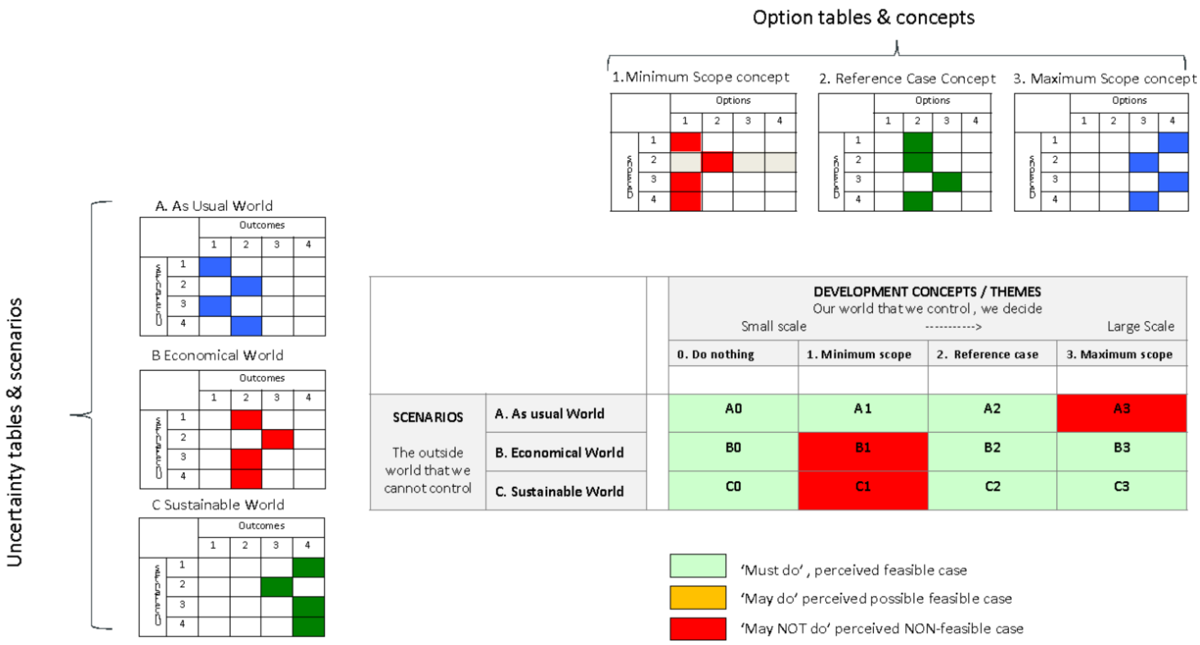

Figure 1 Schematic representation of the Solution Space methodology

The term 'Solution Space' may be portrayed by the area, on one axis defined by the development concepts (decisions inside the sphere of influence of the airport) and on the other axis the scenarios (uncertainties outside the sphere of influence of the airport).

The combination of a development concept and a scenario results in case. Each case is evaluated quantitatively.

3.1.2 Models and other tooling

Energy system models provide a quantitative description of how energy is supplied, converted, transported and consumed within the airport. The effects of intermittent supply and demand and other technical and physical constraints on the airport can be assessed by formulating such an energy model as and optimisation problem.

Calliope is an open-source energy system modelling framework. It is designed to analyse systems with an arbitrary spatial and temporal resolution. The structure, functioning as well as the mathematical description of Calliope are described in the documentation [3]. Calliope consists of linear equation that are optimized by minimizing the annualized total system cost. The amount of storage and usage of energy is included in the optimisation process.

Calliope is a nodal description of an energy network as shown in Figure 2. A 'node' is a specific combination of a 'technology' and a 'location'. A 'technology' is an asset type that produces, consumes, converts, stores or transports energy. A 'location' is a site which can contain multiple technologies. A 'carrier' is an energy carrier that groups 'technologies' in the same network. Finally, a ‘resource’ is a source or sink of energy that can be used by ‘technology’ to add or remove energy to the system.

The system as shown in Figure 2 Schematic representation of the nodal model used to represent an energy system in CalliopeFigure 2 could utilise a ‘resource’ to act as a source for the ‘carrier’ natural gas. This is introduced by a ‘supply technology’ for example a LNG terminal. At the same ‘location’ an empty gas field or a LNG tank could be used as a ‘storage technology’ to store natural gas. The ‘carrier’ natural gas is transported by a ‘transport technology’ for example a pipeline to a different ‘location’. At the other location the ‘carrier’ natural gas can be converted to a different ‘carrier’ such as electricity through a ‘conversion technology’ such as a power plant. ‘Technologies’ at the same location don’t need ‘transport technologies’ to be connected to the same network such as the ‘supply’ and ‘storage technology’ in Figure 3. Finally the ‘carrier’ electricity can be transported through another ‘transport technology’ for example HV transmission lines to another location where a ‘demand technology’ for example an airport. This ‘demand technology’ utilises a ‘resource’ to act as a sink for the ‘carrier’ electricity.

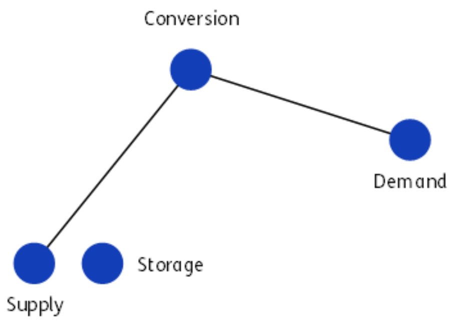

Figure 2 Schematic representation of the nodal model used to represent an energy system in Calliope

Figure 3 presents a high-level description of the in- and outputs of the Calliope model. The technical and economic parameters are used to define the different ‘technologies’ in the model. Resource availability is typically a time series used to define the source or sink of a ‘supply’ or ‘demand technology’ at a time step. The ‘locations’ are defined by the spatial definition, this defines which ‘technologies’ are location where in the model. Model constraints are added to the model to limit the solution of the model. For example, a constraint can be used to define the installed capacity of a certain ‘technology’.

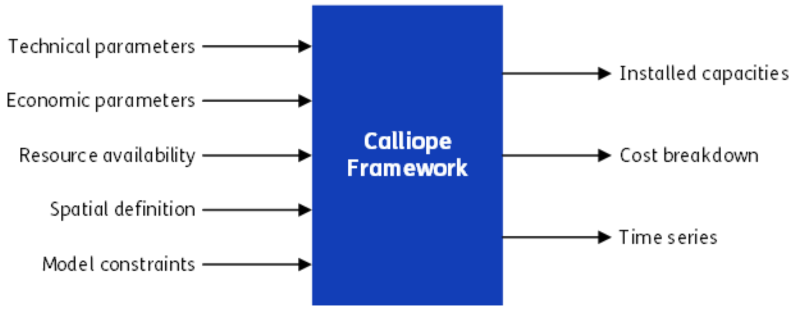

Figure 3 Schematic representation of the in- and outputs of the Calliope model

3.2 Scenarios and solution pathways

This section introduces the energy system at Schiphol Airport and describes the scenarios and development concepts assessed in this study.

3.2.1 Introduction to the airport energy system

3.2.1.1 Introduction to the airport energy management system

As mentioned above the long term goals for the Royal Schiphol Group are to become Net Zero by 2030 and Energy Positive in 2050. Zero-emissions airports Schiphol Group's four Dutch airports are on track to become zero emissions airports by 2030. The Energy Management System (EnMS) of the Royal Schiphol Group is ISO 50001 (Energy Management) certified since 2021. The scope of the EnMS encompasses the airports of Amsterdam Schiphol, including the commercial real estate, Rotterdam the Hague Airport, commercial real estate of Rotterdam Airport, Eindhoven Airport and Lelystad Airport[7].

The EnMS of RSG facilitates the improvement of the energy performance of our airport. The scope of the EnMS is applicable for the airport activities that fall under the responsibility of the RSG organisation.

3.2.2 Energy system scenarios

The aviation background scenarios that were provided by the used AEOLUS model (Aeolus 2022) as outlined in section 3.3, were used as explorative scenarios in this study. None of the scenarios analysed by the AEOLUS model contained a case where the number of flights is reduced. Even if policies restricting the number of flights at Schiphol have not yet been implemented in policy, it has been discussed to lower the number of flights to 460.000 flight movement per year. To highlight the

[7] For a detailed description of the Energy Management System we refer to the EnMS handbook "EnMS-0100 - Handboek Energiemanagement systeeem SNBV 2.2, 2023".

awareness of this study on the potential decrease in number of flights, the low case in the AEOLUS model is referred to as a mid-case for the remaining part of this study.

This study works with two milestone years: 2030 and 2050. Not only are these years used to set deadlines to goals, these two years also provide two different perspectives: a short-term perspective and a long term perspective. The short-term perspective is important, as decisions need to be made now, or as soon as possible, to stay on track. This limits the option space, but also reduces the uncertainty of key developments relevant to Schiphol, such as the development of aviation or the price of electricity. The longer term is more uncertain but provides more time for Schiphol as well as the rest of the world to develop. Both perspectives have their added value and should be used as such.

Table 1 Scenarios for Flight movements, PAX and Freight for 2030 and 2050

	Mid	High
2030	Flight movements: 500,000	Flight movements: 665,839
	PAX: 99,693,629	PAX: 119,490,122
	Freighter movements: 28,376	Freighter movements: 18153
	Freight: 1,529,873 mt/a	Freight: 1,585,252 mt/a
2050	Flight movements: 500,000	Flight movements: 903,120
	PAX: 99,693,629	PAX: 188,998,792
	Freighter movements: 24,077	Freighter movements: 6,324
	Freight: 1,574,185 mt/a	Freight: 2,339,047 mt/a

3.2.3 Technological and non-technological solution pathways

To explore different configurations, four development concepts have been developed. Namely, current policy, solar, wind and hydrogen. Current policy aims to capture the current direction but is in no way reflective of Schiphol Groups current strategy. Table 2 presents the technological solutions available to the different development concepts for electricity generation. For current policy 21 MWp of solar will be deployed in 2030 either on rooftop or in-field. Towards 2050 this will be increased to 200 MWp. The remaining electricity demand will be procured on the market. The solar development concept reflects an increased deployment of solar PV. The wind development concept reflects a wider portfolio where offshore wind is more directly contracted. The hydrogen development concepts does not deploy any renewables and instead relies on a hydrogen-fired CHP and the grid for electricity demand.

Table 2 Selected electricity generation technologies for each development concept in different scenarios, ○ = not applicable

	Current Policy		Solar		Wind		Hydrogen	
Technology	2030	2050	2030	2050	2030	2050	2030	2050
Utility-scale solar PV	21 MWp	200 MWp	75 MWp	300 MWp	21 MWp	100 MWp	○	○
Rooftop solar PV			○	○			○	○
Offshore Wind	○	○	○	○	100 MW	> 200 MW	○	○
Hydrogen CHP	○	○	○	○	○	○	100 MW	300 MW
Import gridmix	150 MW	150 MW	150 MW	100 MW	50 MW	0 MW	50 MW	0 MW

Table 3 presents the available technologies for heat generation. Current policy mostly provides heat through the deployment of building-based heat-pumps supported by some e-boilers for peak capacity. The solar development concepts reflects a more centralized conversion through utility-scale heat pumps and e-boilers. Besides, the conversion of electricity to heat, the solar development concept deploys utility-scale solar thermal. The hydrogen development concept does not have any power-to-heat technology and instead relies on hydrogen-fired boilers. All development concepts allow for the deployment of gas-fired boilers at third-parties and the deployment of building-based heatpumps (and e-boilers) at centrum.

Table 3: Selected heat generation technologies for each development concept in different scenarios, ○ = not applicable, ● = technology available, ◐ = technology only available at selected locations.

	Current Policy		Solar		Wind		Hydrogen	
Technology	2030	2050	2030	2050	2030	2050	2030	2050
Utility-scale heat pump	○	○	●	●	○	○	○	○

Building-based heat pump	[black]	[black]	[red]	[red]	[black]	[black]	[grey]	[grey]
Utility-scale heat pump (water-based)	[grey]	[grey]	< 20 MW	< 20 MW	[grey]	[grey]	[grey]	[grey]
Utility-scale solar thermal	[grey]	[grey]	25 MW	150 MW	[grey]	[grey]	[grey]	[grey]
Rooftop solar thermal	[grey]	[grey]	[grey]	[grey]	[grey]	[grey]	[grey]	[grey]
Utility-scale e-boiler	[grey]	[grey]	[black]	[black]	[grey]	[grey]	[grey]	[grey]
Building-based e-boiler	[black]	[black]	[red]	[red]	[black]	[black]	[grey]	[grey]
Utility-scale hydrogen-fired boilers	[grey]	[grey]	[grey]	[grey]	[grey]	[grey]	[black]	[black]
Building-based hydrogen fire boilers	[black]	[black]	[grey]	[grey]	[grey]	[grey]	[black]	[black]
Gas-fired boilers	[red]	[grey]	[red]	[grey]	[red]	[grey]	[red]	[grey]

Table 4 presents the technologies available in the development concepts at airside. Current policy has fixed power units at the gate and eGPUs at remote positions. Towing is envisioned to be powered through hydrogen. In the solar concept all airside demand, including towing is electrified. In the wind concept gate positions are also serviced by eGPUs. In contrast, in the hydrogen concept all airside technologies are hydrogen-powered.

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Table 4 Selected airside technologies for each development concept in different scenarios, ○ = not applicable, ● = technology available, ◉ = technology only available at selected locations

	Current Policy		Solar		Wind		Hydrogen	
Technology	2030	2050	2030	2050	2030	2050	2030	2050
eGPU at remote positions	●	●	●	●	●	●	○	○
eGPU at gate positions	○	○	○	○	●	●	○	○
FPU at gate positions	●	●	●	●	○	○	○	○
H2GPU at remote position	○	○	○	○	○	○	●	●
H2GPU at gate position	○	○	○	○	○	○	●	●
e-towing	○	○	●	●	●	●	○	○
H2-towing	●	●	○	○	○	○	●	●

Table 5 presents the infrastructure available in the different development concepts. Current policy allows for the deployment of additional electrical infrastructure and the introduction of hydrogen. The solar concept deploys more centralized power-to-heat technologies, hence heat grid are required to transport the heat to the location of demand. In the hydrogen concept, heat grids are also available to transport the heat from the CHP to the location of demand.

Table 5 Selected infrastructure technologies for each development concept in different scenarios, = not applicable, = technology available, = technology only available at selected locations.

	Current Policy		Solar		Wind		Hydrogen	
Technology	2030	2050	2030	2050	2030	2050	2030	2050
Electrical	available	available	available	available	available	available	available	available
Heat grid	not applicable	not applicable	available	available	not applicable	not applicable	available	available
Hydrogen	available	available	not applicable	not applicable	not applicable	not applicable	available	available

Table 6 presents the different storage technologies available to the different development concepts. Current policy does not deploy any storage technologies. In the solar case, electrical storage is deployed in tandem with solar PV, but the kind of storage is not set. In addition, thermal storage is deployed in tandem with solar thermal. The wind concept allows all storage technologies, but does not set the capacity. In the hydrogen case, only storage of heat is allowed.

Table 6 Selected storage technologies for each development concept in different scenarios, = not applicable, = technology available, = technology only available at selected locations.

	Current Policy		Solar		Wind		Hydrogen	
Technology	2030	2050	2030	2050	2030	2050	2030	2050
Lithium ion	not applicable	not applicable	> 75 MW eq	> 75 MW eq	available	available	not applicable	not applicable
Redox flow	not applicable	not applicable			available	available	not applicable	not applicable
Thermal energy storage	not applicable	not applicable	> 25 MW eq	> 25 MW eq	available	available	available	available

3.3 Modelling framework implementation

This subsection describes how a set of models combined in a workflow have been used to perform the study. First an overview of the model workflow is given and how these models work together. Then the models are shortly discussed individually, after which the implementation development concepts and scenarios as in the Calliope model are discussed. Finally, a subsection on model uncertainties describes how the chosen approach should address model uncertainties.

3.3.1 Modelling framework description

At the heart of the model workflow is the Calliope model. This is an energy system model ideally suited for simulating the developments within an energy system in a complex, sector coupled environment such as Schiphol. The model can work with a high temporal resolution, can handle problems with a spatial dimension and is flexible to handle a wide range of technologies. Calliope is an optimization model and is able to optimize both the operations of the system (when to activate which technology) as well as the configuration of the system (which technology to install) based on capital and operation costs.

3.3.1.1 Calliope as central model

Calliope is a techno-economic model that combines technical aspects of an energy system, namely the provision of energy, with the economic aspects. As outlined in Section 3.1 the Calliope model requires technical and economic parameters, resource availability, spatial definition, and model constraints. The resource availability sets both the energy availability as well as the energy demand in the Calliope model.

For Schiphol, developments in two areas have most impact on the overall energy demand. In the reference year, buildings at Schiphol have the highest energy demand in the form of heat and electricity (and cooling, which is not modelled explicitly but is part of the electrical load) and will remain significant in the future. Over time though, the largest change in energy demand is expected to take place in airside operations. The Aeolus model provides insight in the development of the number of PAX and flight movements. Figure 4 presents a high-level overview of the model workflow to translate the output of Aeolus model to input of the Calliope model. In this figure, solid arrows indicate a direct dependency whereas striped arrows indicate indirect dependency. Here, an indirect dependency describes a non-linear dependency.

The Aeolus model was used to determine the number of PAX and flight movement based on Dutch policy and economic developments. The Calliope model requires energy demand as an input. Thus, the number of PAX and flight movements need to be converted to foreground scenarios, which are a set of energy demand time series which can be used to the Calliope model. To limit the number of test cases, for all other uncertainties a single reference scenario was defined for each year 2030 and 2050. Developments in the field of landside mobility (most notably charging of electric vehicles and trucks of passenger and freight handlers) was left outside of the modelling scope.

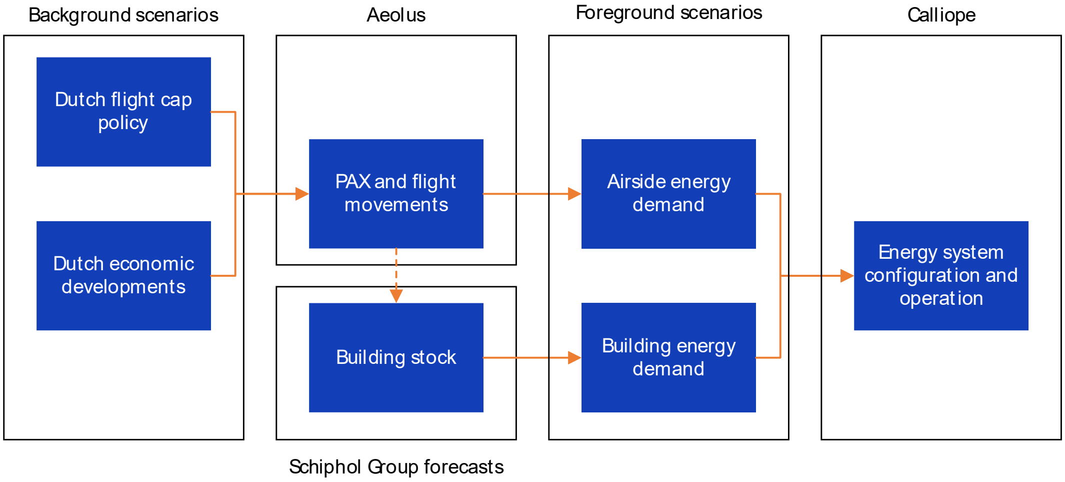


Figure 4 High level description of the modelling workflow

3.3.1.2 Airport Model

To support quantification of the foreground scenarios (energy demand in future moments in time and at each location) based on these background scenarios, a conversion is needed. This conversion is done by the Airport model. This Excel sheet can translate the change in number of flight movements and passengers at Schiphol available from the Aeolus dataset into growth numbers of the energy demand for future years for each scenario. Because of the significant difference in capacity and energy demand, two aircraft types were distinguished: narrow and wide bodies. Based on the total number of annual passengers and flight movements, typical narrow body and wide body pax capacities and historic occupancy rates, the ratio between nabo and wibo aircraft was derived. Then, using the flight schedule of the reference year, these annual totals were converted to high resolution time profiles at each location. Similarly, the development in building stock was combined with historic metered gas and electricity profiles to generate location specific demand profiles. The anticipated developments in the built environment were quantified in terms of change in gross floor area (m2) and this data was provided by Schiphol for 2030 and 2050.

3.3.1.3 Technical and economical parameters

Besides resource availability (and demand), the Calliope model requires technological and economic parameters. Firstly, costs are incurred by the model through investments when determining the optimal configuration of the system quantified by CAPEX and fixed annual OPEX of a technology. Secondly, costs are incurred by the model during operation of the system quantified by variable (V)OPEX, which typically represents procurement costs of energy. The modelling workflow is described in Figure 5 Schematic representation for the modelling workflow.

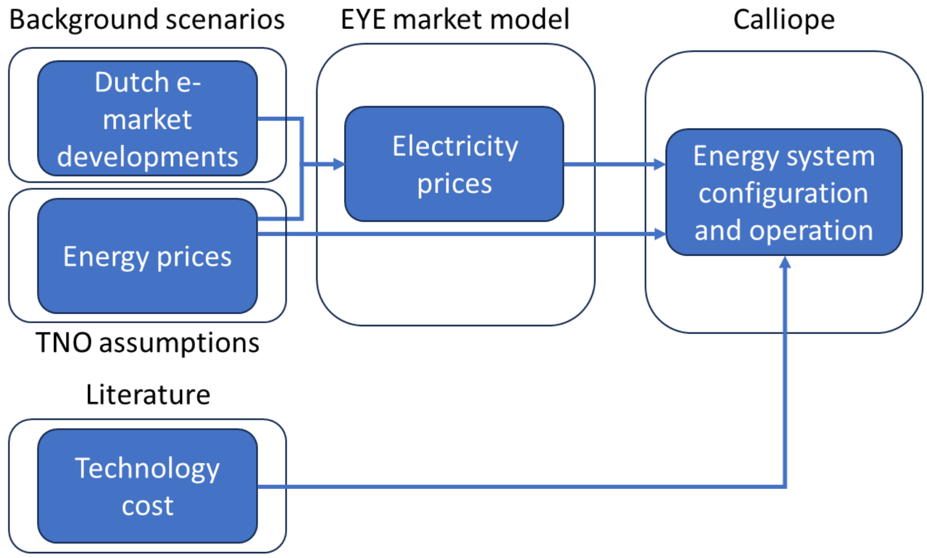


Figure 5 Schematic representation for the modelling workflow

The technology cost data was obtained from online sources. While some of these sources provide different cost indications for different years, it was decided to adopt only the cost data for 2030 to reduce the uncertainty that is related to such assumptions. All assumptions can be found in several assumption sheets added in Appendix.

3.3.1.4 Energy prices

Five energy carriers are relevant to the Schiphol case: natural gas, diesel, kerosine, hydrogen and electricity. As assets running on diesel and kerosine are assumed to be phased out by 2030, only historic price data is required for the reference year. For natural gas and hydrogen, price assumptions are made reflecting annual average values for 2030 and 2050 based on TNO expertise. In the reference year, Schiphol procured its gas with long term contracts, and it is assumed that gas supply will remain under long term contracts until 2030. The same construction is assumed for hydrogen procurement; hence a fixed average hydrogen price is assumed for 2030 and 2050.

3.3.1.5 Electricity prices

On electricity markets, price volatility can be observed on an hourly basis, and it is expected to increase in the next decades with increasing penetration of renewables. While Schiphol is currently still under contract with an energy supplier, considering the development potential of electricity production and storage, in this study it is assumed that Schiphol becomes an electricity market player with direct access to electricity market trading. This provides the opportunity to evaluate the value of flexibility on Schiphol in terms of electricity procurement, and the value of supply of any (residual) electricity production back to the grid.

To obtain these hourly electricity prices, the TNO inhouse electricity market model EYE was used. This model simulates the Dutch electricity spot market, calculating the clearing price of electricity based on supply and demand at each hour in a year. For consistency, the same assumptions for gas and hydrogen prices were used in the EYE model as in the Calliope model. The weather profiles for offshore wind were aligned as well.

Besides energy prices, EYE requires the installed capacities of participating assets on the electricity market. For 2030 existing scenarios were used based on the Dutch Climate Agreement readily available within TNO. These assumptions include increasing installed capacities of onshore and offshore wind farms, solar panels (both roof-top and utility scale farms), storage facilities, and hydrogen-fired thermal power plants, as well as reduction of fossil fuel based thermal power plants running on gas and coal.

For 2050, a scenario was drafted based on TNO expertise assuming further development of wind, solar and flexible demand like power-2-heat, as well as introduction of hydrogen-based electricity production as replacement for existing natural gas plants. While the uncertainty of the electricity prices for 2030 is deemed quite low, the uncertainty for 2050 is very high. The path towards a fully renewable electricity system is not yet defined by the Dutch government and several (emerging) technologies can have significant impact once deployed, while the chance of deployment is difficult to predict.

Since significant production of electricity by Schiphol is part of any development concept in 2050, thereby reducing the dependency on the electricity grid, the uncertainty of the 2050 electricity market scenario is deemed to be acceptable. Concerning sales of electricity to the market, we have observed that this impact can be much more significant, for example when investment decisions are made purely to sell to the grid. For this reason, any revenue from electricity sales to the market is accounted for in the model but does not contribute to the optimization. In other words, there is no incentive for the model to base investment decisions on the electricity price.

Similarly to the revenue, CO2 emissions are accounted for in the model, but do not contribute to the cost objective function. Typically this is the case using a CO2 (ETS) price, but given the goal formulated by Schiphol to phase out emissions from their airside, with the result that the only modelled emissions are those of gas boilers in 2030, with many different parties involved of whom it is uncertain whether they will fall under the ETS by then, it was decided to leave CO2 cost out of the equation. In the EYE model, the ETS price is included for 2030.

3.3.2 Airport energy system model implementation

As outlined previously, each individual combination of a development concept and a scenarios forms a case. All cases combine outline the solution space.

3.3.2.1 Implementation of development concepts in Calliope

The development concepts were implemented in Calliope by selectively changing the constraints around the key technologies that define each concept, for example whether airside assets are hydrogen or electricity powered, or whether renewable electricity is mostly produced from wind turbines or solar panels. These constraints are tailored for each year to introduce implicit constraints. Most notable implicit constraints are the limited capacities of renewables and storage assets in 2030 to prevent infeasible amounts of deployment considering typical lead times of wind and solar projects and the state of the stationary battery supply chain which currently (2024) would not be able to supply GWhs of electricity storage systems. Another notable implicit constraint is the complete absence of any fossil fuel-based airside asset in 2030, reflecting the policy goal of Schiphol to phase such assets fully out from their airport.

Concerning the explicit constraints, three types are used:

- Fixed at specific capacity (can also be zero), typically used for technologies that define a development concept.
- Minimum or maximum capacity: force a minimum or maximum capacity but leave it to the model to adjust this capacity below or above this threshold, typically used when unwanted behaviour is expected, such as too high or too low capacities.
- Completely open: leave it to the model to decide,

For area intensive technologies like PV, area constraints were used to make sure that the maximum area available at a location is not exceeded. This is especially important for e.g. building roofs, but also relevant for open fields. These area constraints are the same for each development concept but differ per scenario year. By combining the node specific area constraint (telling the model to install no more than X ha at a specific location) with the system generic capacity constraint (telling the model to install X MW at Schiphol), the model is allowed to distribute the PV capacity over several locations as optimally as possible. This trade-off may include choosing between cheaper deployment on land, or deployment on roof where the distance to the consumer is shorter, saving infrastructure cost. Similarly, buildings with cooling electricity demand may be preferred over buildings with a more baseload profile.

To accommodate new utility scale energy technologies, some new locations are assumed. These so-called energy hotspots represent areas or facilities that currently do not make up any part of the Schiphol energy infrastructure, but would need to be developed by Schiphol when deploying utility scale PV farms with centralized electricity storage, heat grids with centralized heat production and storage or cogeneration with CHP plants. Especially PV farms require large plots of lands, but also MW scale energy facilities will require significant space. Three on-site locations have been selected in the clusters Schiphol Noord, Zuid-Oost and Oost (airside) with open fields that show sufficient potential for development of such centralized facilities. The Airside energy hotspot represents all available plots of land around and in between landing strips. The energy hotspot on Noord also includes all parking areas that are suitable for carport PV development (most notably long-term parking lot P3). These locations are assumed to become available for 2030 and 2050. To increase the maximum potential of PV for 2050 even further, an offsite solar farm location is defined with additional space for solar power deployment for the Solar concept only. This location represents neighbouring farmland that may be leased by Schiphol. Deployment of PV on this location requires an additional fee for the land lease and is therefore more expensive than onsite deployment.

3.3.2.2 Implementation of scenarios in Calliope

Scenarios are implemented by varying the growth rate of demand at each location in each year as calculated with the Airport model. This growth rate is a multiplier of the timeseries profiles obtained from historic data. This implicitly assumes that the distribution of energy does not change over time and is scaled linearly with the growth rate. Example factors that could alter this distribution, but again was not included in this study, is insulation of buildings or more equal distribution of flights over the day.

See scenario sheets in Appendix for more details on scenarios.

3.3.2.3 Mobile assets definition, operations and charging in Calliope

One of the challenging aspects of implementation of the Schiphol case was including BEV mobile energy assets such as tow trucks, GPUs, PCUs and GSE. Calliope cannot deal with varying capacities during a single simulation, such as assets that can either move between two locations, or assets that are disconnected from the energy grid when used in operations. Also, the number of BEV units may change depending on scenario or optimization by Calliope, so the number of assets cannot be individually implemented. This would also blow up the number of nodes required. Lastly, the charging capacity may differ from the discharge capacity, whereas in Calliope an asset can only have one capacity (both for input and output).

To overcome these issues, mobile units were split up into two separate assets: one for the battery and with a capacity equal to its charge capacity, and one for the engine with a capacity equal to the discharge power of the relevant activity (e.g. towing, ground power etc). Then, manual constraints were added to the numerical model to ensure the following.

Firstly, when an asset is being charged, it cannot be used (discharge) in operations, and vice versa. This was done by constraining the input power of the battery according to the output power of the battery at each timestep. For example, when 10 E-GPUs are deployed and 7 are in use, the input power to the battery can be no more than the equivalent of 3 E-GPUs.

Secondly, the ratio between the storage (battery) and conversion tech (engine or convertor) is fixed according to the power required for an activity and the power with which the asset can charge. For example, 50 kW chargers were assumed for Nabo E-GPUs, each of which can provide a single of

28.8 kW of power. The ratio will be kept equal, so if Calliope wants to install more than the minimum required to supply the demand, this ratio is maintained.

Thirdly, all electricity that is supplied by the charger to a location needs to be consumed by the EV battery first. Only then, the battery may supply the power as demand, obeying the constraints described above. This is to prevent Calliope from bypassing the batteries and directly supplying power from the charger to the demand technology, circumventing the need for batteries but simulating a non-realistic situation.

To implement these constraints, each activity (towing / ground power / preconditioned air / other GSE) was assigned its own location per aircraft type. Calliope is allowed to freely invest in charger capacity, allowing the option to choose the ratio of chargers versus battery vehicles as it sees economically fit.

3.3.3 Handling of model uncertainties

Known issue with optimization is the coin-flip effect: completely different solutions that are only marginally less cost-optimal than the calculated optimal solution, but which are missed in the modelling exercise because the modelers only calculate a single optimal solution. By working with different development concepts, forcing technologies to be absent or present, a range of technological solutions is guaranteed to be part of the solution space. This allows for better understanding why certain choices are better than others based on their relevance within the context of Schiphol.

Remaining uncertainties:

- Use of single reference year
  - Weather
  - Demand
- Extrapolation of energy demand in reference year
  - New buildings same characteristics as current building stock.
  - Building stock scenarios not well tailored to fit aviation scenarios, mostly applicable to 2050.
  - Distribution of flights during day scaled up linearly with increasing flight movements.
  - Future aircraft assumed to be of same type with similar energy demand and similar average occupation (pax per aircraft) as today.
  - Note that a shift in aircraft type was correctly included.
- Prices and costs
  - Hydrogen price.
  - Technology cost no learning curve assumed.
  - Highly uncertain electricity market in 2050.

- Simplifications
    - All gas demand assumed to represent energy demand for space heating. In terms of energy volumes, this assumption seems reasonable, but for capacity estimations in hotels this is probably inaccurate; similarly, process heat at Schiphol Oost is not included correctly, but adverse impact of this assumption on overall system is deemed insignificant.

3.4 Robust smart energy hub concept(s)

In this section, the results of the scenario study for Schiphol Airport are presented. In this study, different development concepts were evaluated for two milestone years: 2030 and 2050.

When interpreting the results, the reader should always keep in mind the fact that when comparing the reference case of 2019 with any future case, multiple things change at the same time. On one hand, we vary the solution space which may impact things like infrastructural requirements (think of onsite solar power versus offsite wind power technology, for example). On the other hand, considering the seemingly unavoidable growth, even if no particular energy solutions are considered, chances are that many aspects of the grid would need to be revised.

3.4.1 Presentation of modelling results

In this chapter the modelling results are presented. To make this result section more readable, the whole energy system is broken up in the following components:

- Electricity subsystem.
- Heat subsystem.
- Airside assets and infrastructure.
- Storage facilities.
- Energy infrastructure.

Ultimately, the results of the integral system are presented. In each subsection, the output of the different development concepts is compared to one another for each year. The scenarios provide a comparison what happens when airside demand increases drastically and can be used to investigate the sensitivity of the concepts with airside demand.

The performance of the development concepts is compared based on the following energy parameters:

- The primary energy consumption: all energy required to provide Schiphol its activities with energy, including external system losses.
- Imported and harvested energy consumption; primary energy consumption of Schiphol, excluding the external losses.
- Total produced energy: all energy produced or converted on Schiphol.
- Final energy demand: all energy that is used effectively by activities on Schiphol.

The following cost parameters are presented:

- Levelized cost of energy.
- Total annual system cost.

3.4.1.1 Electricity

Figure 6 Breakdown of the annual electricity demand for each scenario and development concept presents the electricity demand at the airport for the various development concepts. Most of the electricity demand stems from buildings. This largely encompasses the existing demand from terminals to operate shops, check-in desks, conveyor belts, escalators, lighting, etc. The growth in electricity demand by buildings is most notable in 2030 versus 2019. The key difference in electricity demand is largely made in the electrification of airside activities. Both the solar and wind development concepts introduce e-GPUs and employ electrified taxibots to taxi the aircraft to the runaway and/or gate. Power-to-heat has a lesser contribution to the overall electricity demand. The building demand includes power-to-heat technologies currently already deployed at Schiphol Airport. Hence, the power-to-heat category only includes additional deployment of power-to-heat. The electricity demand differs for each case, this is due to a difference in installed capacity of heat pumps and e-boilers. Load shedding is negligible across all development concepts.

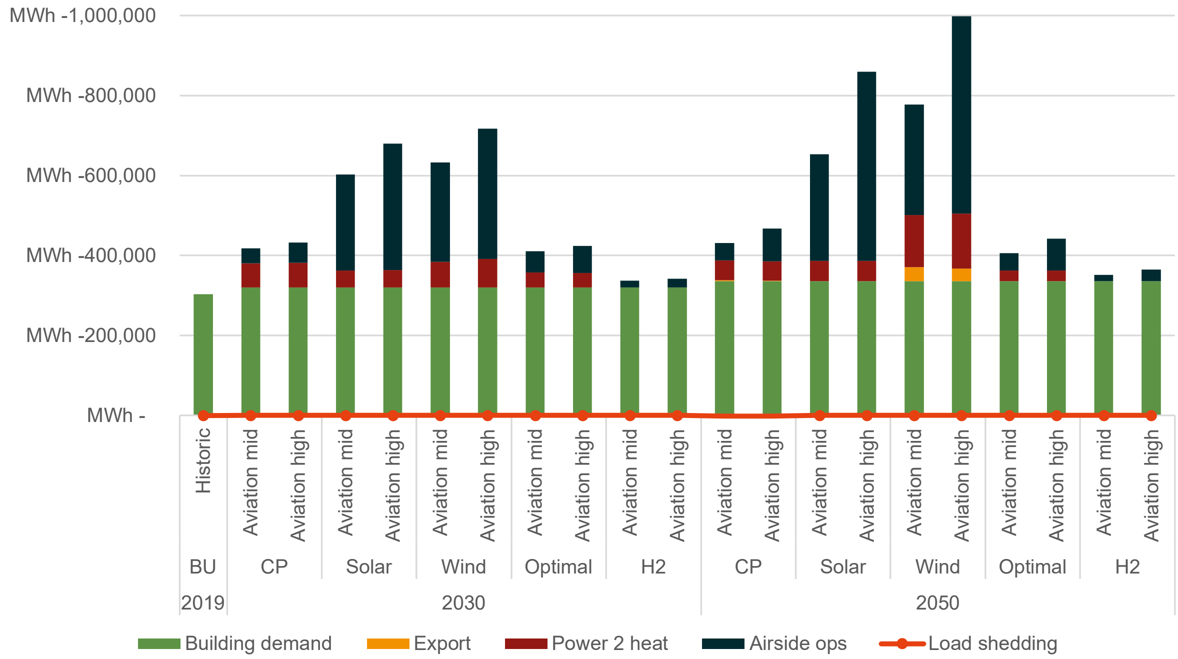


Figure 6 Breakdown of the annual electricity demand for each scenario and development concept

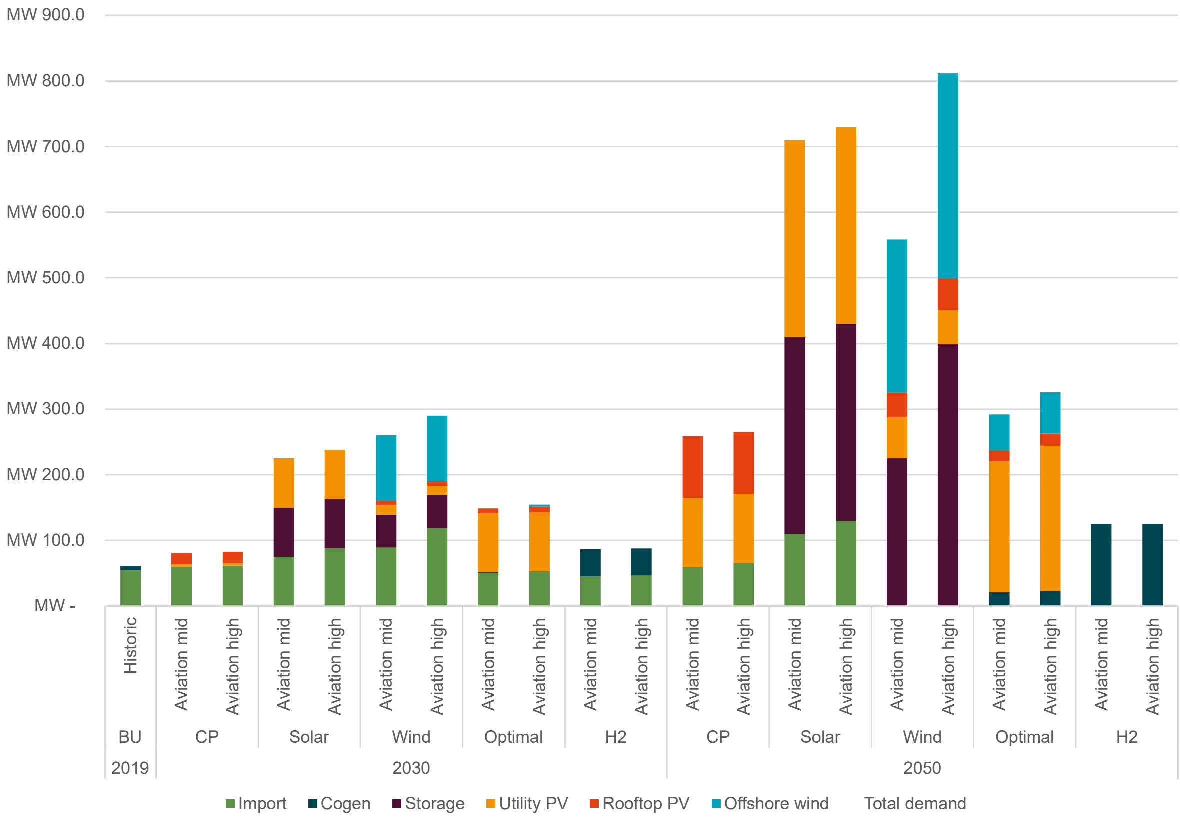


Figure 7 Breakdown of the installed capacity electricity generation assets per asset type for each scenario and development concept

To meet electricity demand in the different development concepts, the electricity is either generated on-site or imported through procurement on the market. Figure 7 shows the installed capacity of generation assets on-site and the import capacity, in Figure 8 the electricity generated with these assets is shown.

Installed capacities of generation assets have largely been defined by the constraints of the development concepts. In the solar cases, 75 MWp of utility-scale solar PV is deployed in 2030 and 300 MW in 2050. Likewise, the 2030 wind case, 100 MW offshore wind is deployed in tandem with 21 MWp of solar PV. In the 2030 wind case, the cost optimisation is able to select where to deploy the PV panels. In both ‘aviation mid’ as well as ‘aviation high’ this results in about 14 MWp deployed on utility-scale and 7 MWp on rooftops. In the 2050 wind case a similar distribution can be observed.

The difference in the aviation high and aviation mid scenarios is most notable in the wind development concept, stretching the installed capacity from 550 MW to 800 MW. In the aviation high scenario almost 200 MW of storage is required.

A significant amount of storage is required in both the solar case and the wind case in 2050. In the both the wind and solar concepts this is a constraint and deployed in a set ratio. The cost optimisation results almost predominantly in the deployment of redox flow batteries.

In the optimal case, the model opts for the deployment of 90 MW utility-scale PV in tandem with 7 to 8 MW of rooftop PV in 2030. In 2050, the optimal case opts for a similar range of assets with 200 to 220 MWp utility-scale PV, 16 to 18 MWp of rooftop PV but with the addition of 55-63 MW of offshore wind and a hydrogen cogeneration unit of 50 to 55 MW.

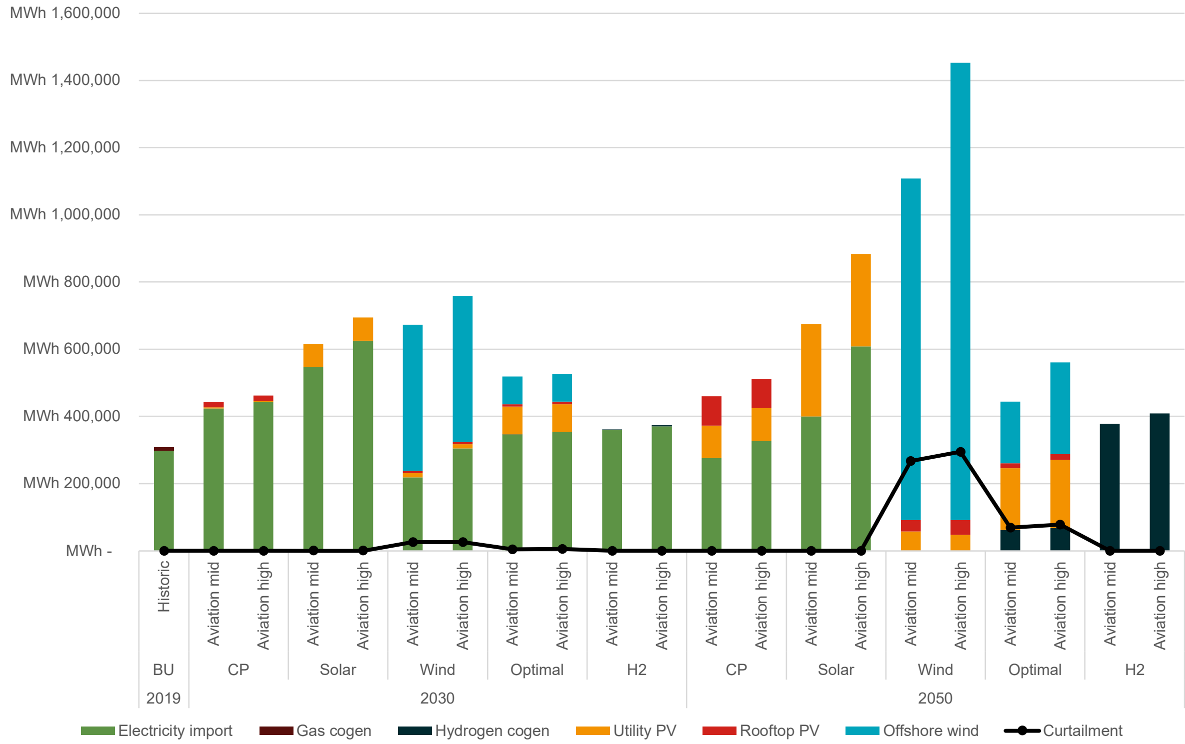


Figure 8 Breakdown of the electricity generated per asset type for each scenario and development concept

Figure 9 presents the levelized cost of electricity in all cases. Both the levelized cost on the supply side as well as the demand side is presented. A difference in these levelized costs indicated losses in the system. Figure 10 presents the breakdown of the annual cost for electricity, which provides insides in the main cost constituents of the levelized cost. Table 7 provides the average LCOE for the most relevant assets in 2030 and 2050. In 2030, the cost of utility-scale solar and offshore wind is lower than the average market cost. The cost of rooftop PV is similar to the average market cost and would need to benefit from reduced infrastructure costs to warrant deployment.

Table 7 Average levelized cost for generation assets in the different development concepts

Asset	2030	2050

Utility-scale PV	52.6 EUR/MWh	52.6 EUR/MWh
Rooftop PV	73.1 EUR/MWh	73.1 EUR/MWh
Offshore wind	52.6 EUR/MWh	52.6 EUR/MWh
Market	70.5 EUR/MWh	105.1 EUR/MWh

For the solar development concept in 2030 only a limited amount of power is generated through solar PV. Hence the overall cost of electricity is largely determined by the cost of electricity on the market. The overall levelized cost is higher than the market cost due to the cost of storage and infrastructure, as shown in the annual cost breakdown. In 2050, a similar trend can be observed although the cost of storage is more dominant.

For the wind development concept in 2030 the majority of the electricity is generated by offshore wind. Although the levelized cost of wind is lower than the grid mix, infrastructure and storage requirements increase the annual cost. In 2050, the airport is operated only on wind, the main constituent of the overall cost besides generation is the cost of storage.

The hydrogen cases in 2030 operate the hydrogen fired CHP only a few moments in the year. Most electricity is imported from the grid where gas-fired powerplants still operate. The use of the hydrogen-fired CHP substantially increases in 2050 where the cost of hydrogen is assumed to have fallen and the grid is decarbonised (only hydrogen-fired dispatchable assets remain).

The optimal case in 2030 relies strongly on the market to provide electricity whereas in 2050 it relies on a portfolio of offshore wind and solar PV. In addition, the cost optimisation result in the deployment of a hydrogen-fired CHP to produce electricity during periods of low renewable electricity production instead of storage solutions.

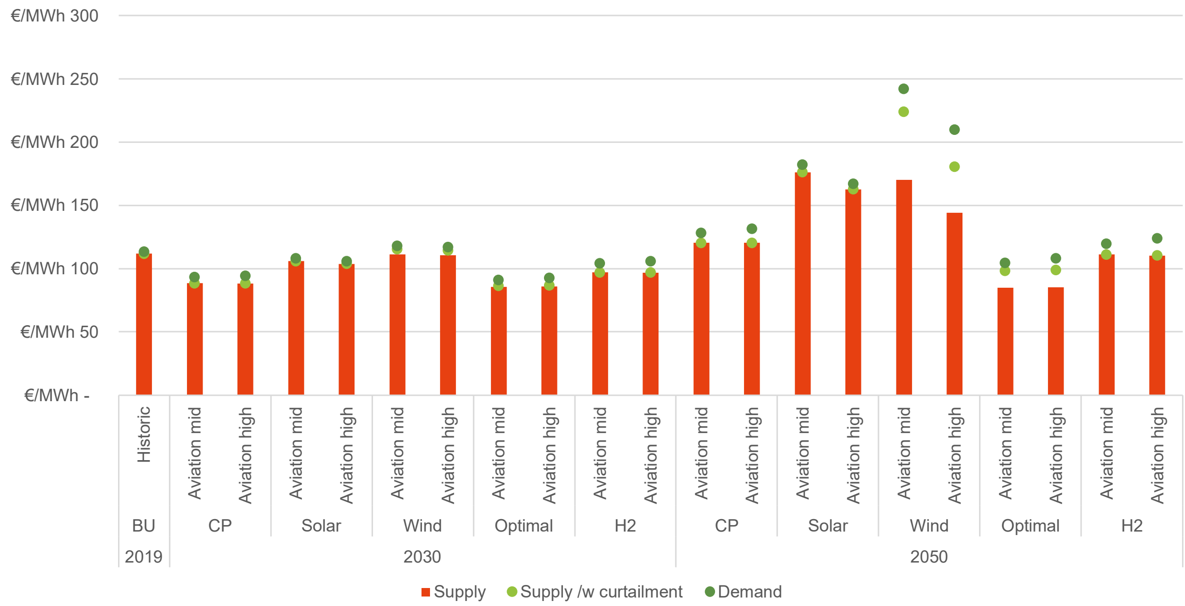


Figure 9: Levelized cost of electricity for each scenario and development concept

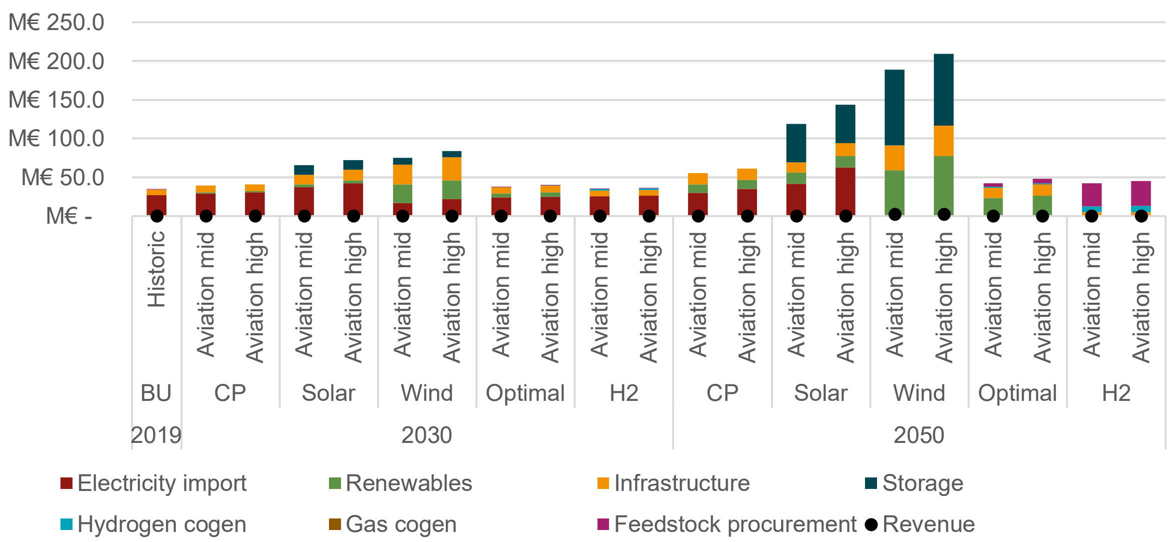


Figure 10: Breakdown of annual costs for electricity production for each scenario and development concept

3.4.1.2 Heat

Figure 11 presents the heat demand at the airport for the various development concepts. The majority of the heat demand stems from buildings. This building based demand covers heat demand for space heating, tap water heating and some process activities.

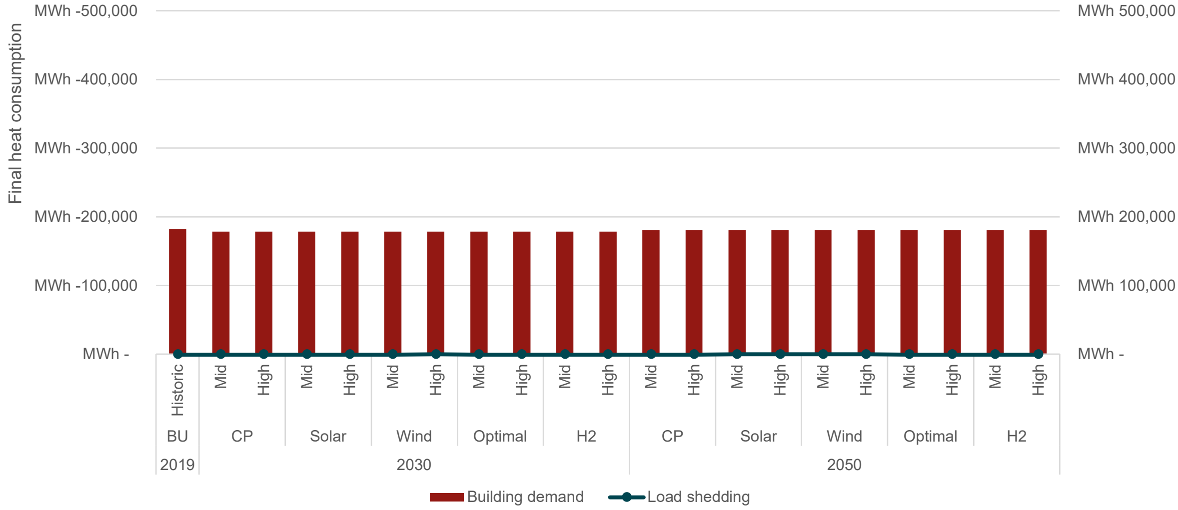


Figure 11: Breakdown of the annual heat demand for each scenario and development concept

Figure 12 shows the installed capacity of heat production assets. The solar cases, especially in 2050, have the largest installed capacity. This is largely due to a combination of solar thermal of 150 MW and an equivalent amount of thermal energy storage. This installed capacity is set by the constraints of the solar development concept. Likewise the installed capacity for the hydrogen co-generation is set by the constraints of the hydrogen development concepts. The installed capacity of heat pumps and eboilers is determined by Calliope. These assets should be considered as operating in tandem, where eboilers provide flexibility to provide demand during peak moments and heat pumps supply the baseload. Typically, the installed capacity of heat pumps is larger than the installed capacity of eboilers. Exceptions provide heat through other assets such as solar thermal with thermal energy storage. The total installed capacity increases almost all development concepts in comparison to business as usual in 2019. This is due to a lower capacity factor for the total heating system. The amount of load-shedding is negligible for all development concepts.

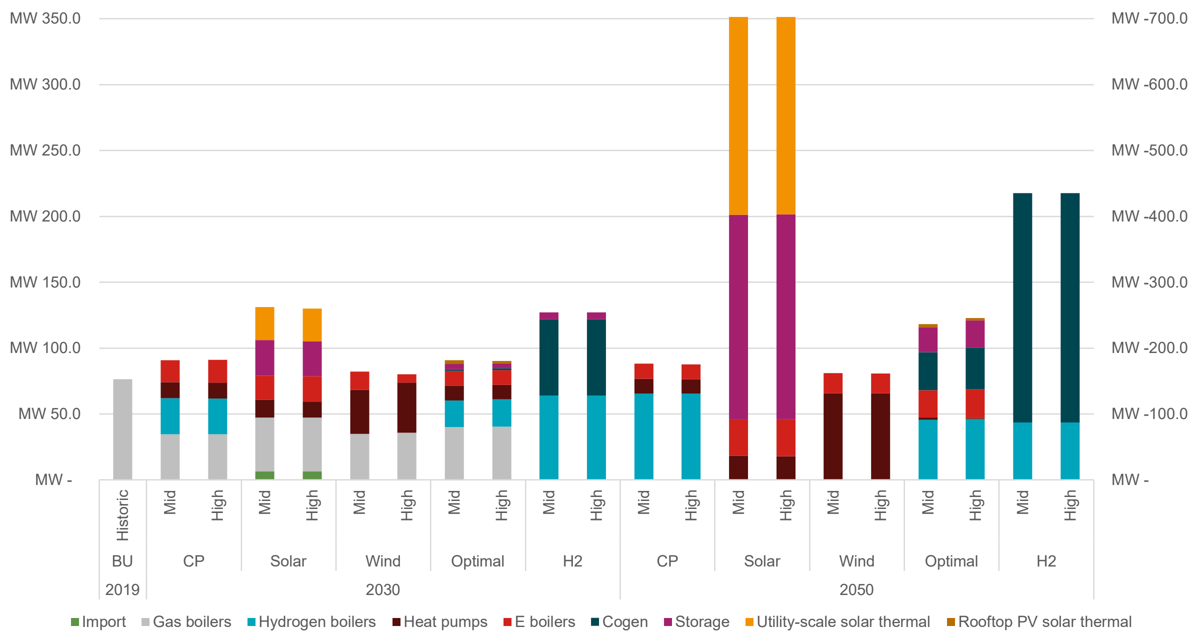


Figure 12: Breakdown of the installed capacity for heat generation assets per asset type for each scenario and development concept

Figure 13 shows the heat production for all development concepts. Most development concepts meet the heat demand with little curtailment. However, curtailment is very significant in the 2050 hydrogen case and to a lesser extend in solar 2050 case. In the hydrogen case, a large part of the heat production is curtailed. The heat produced by the co-generation unit is largely curtailed and hence the co-generation is mostly utilised to produce electricity only. The hydrogen case in 2040 differs in the amount of curtailment as very little electricity is generated with the co-generation unit. Some curtailment of solar thermal heat is present in the 2050 solar case during periods of heat production but little heat demand with thermal energy storage assets largely filled. In the other development concepts most heat is provided sustainably through heat pumps with the exception of the wind 2050 case.

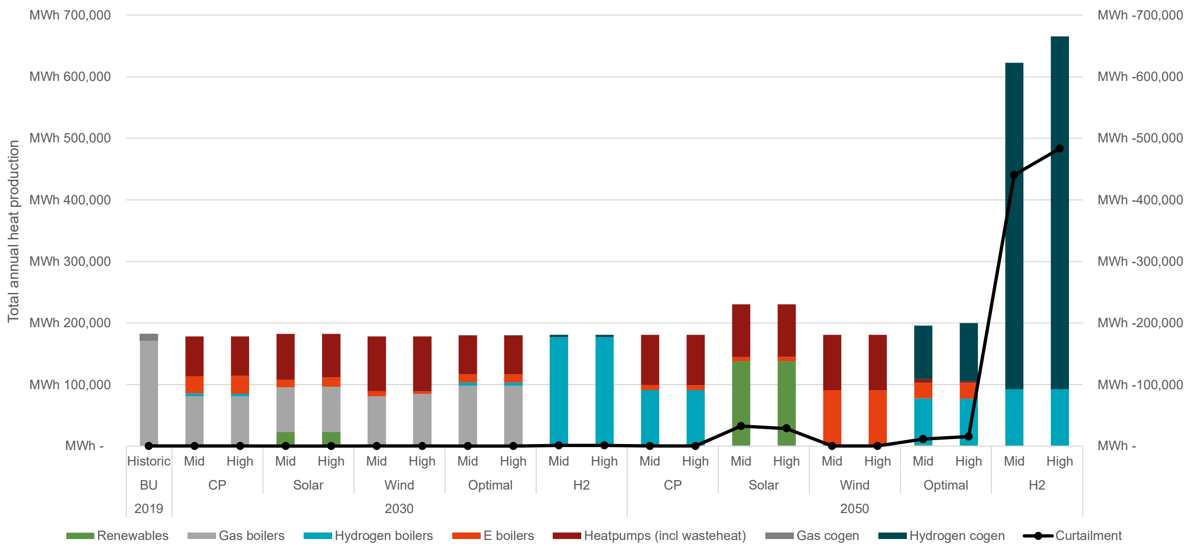


Figure 13: Breakdown of the heat generated per asset type for each scenario and development concept

Figure 14 shows the primary energy demand for the various development concepts. All development concepts with heat pumps indicates that heat pumps contribute significantly to the reduction of primary energy demand. In contrast, hydrogen use increases the primary energy demand significantly.

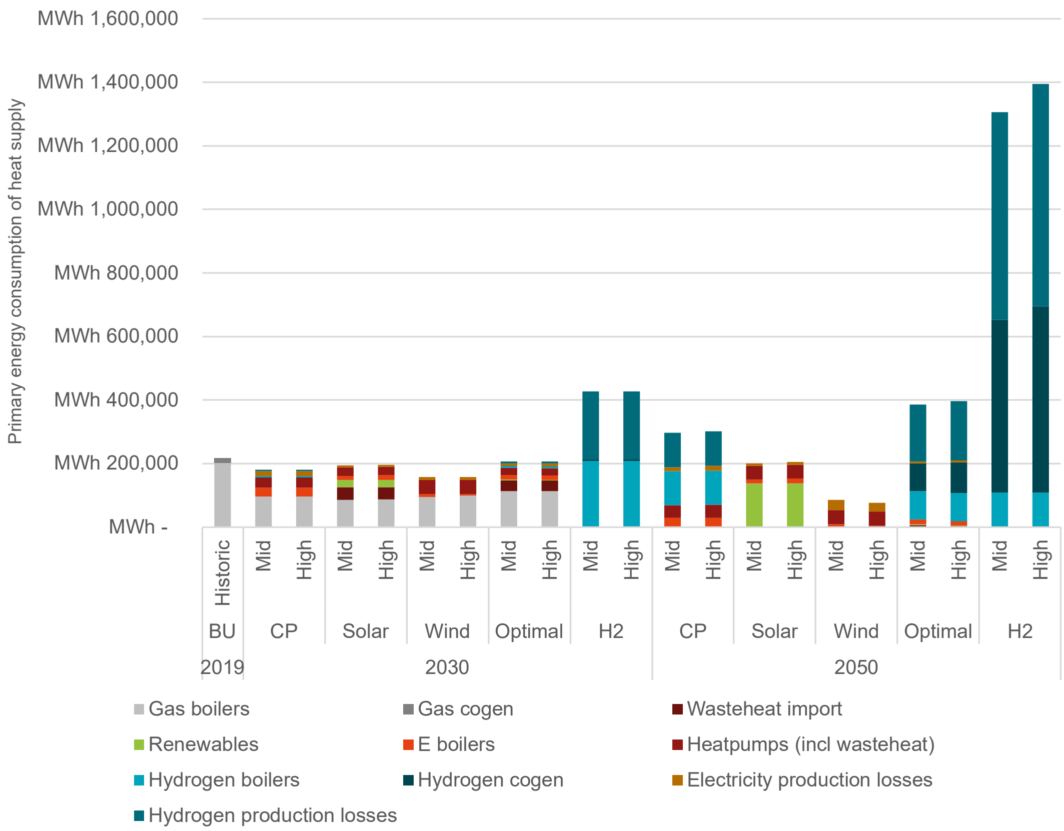


Figure 14: Breakdown of the primary energy demand per asset type for each scenario and development concept

Figure 15 shows the levelized cost of heat for the different development concepts whereas Figure 16 presents a breakdown of the annual cost. In 2030, the wind case and the hydrogen case result in higher levelized cost of heat in comparison to the solar and optimal case. The wind case relies on larger installed capacity of heat pumps which collectively have a lower capacity factor than in the solar case. Together with the higher levelized cost of electricity this results in an overall higher cost of heat. Likewise, the optimal case results in a LCOH since the LCOE is lower in comparison to the other cases in 2030. The hydrogen case results in higher cost due to the relatively costly feedstock, especially in 2030. Overall the 2030 result in higher LCOH in comparison to business as usual case in 2019. The replacement of natural gas by other more costly feedstocks (electricity and hydrogen) results in higher levelized costs. Similar trends can be observed in 2050. The LCOH of supplying heat is relatively low for the hydrogen 2050 case. However, curtailing a large amount of heat does lead to comparatively costly LCOH.

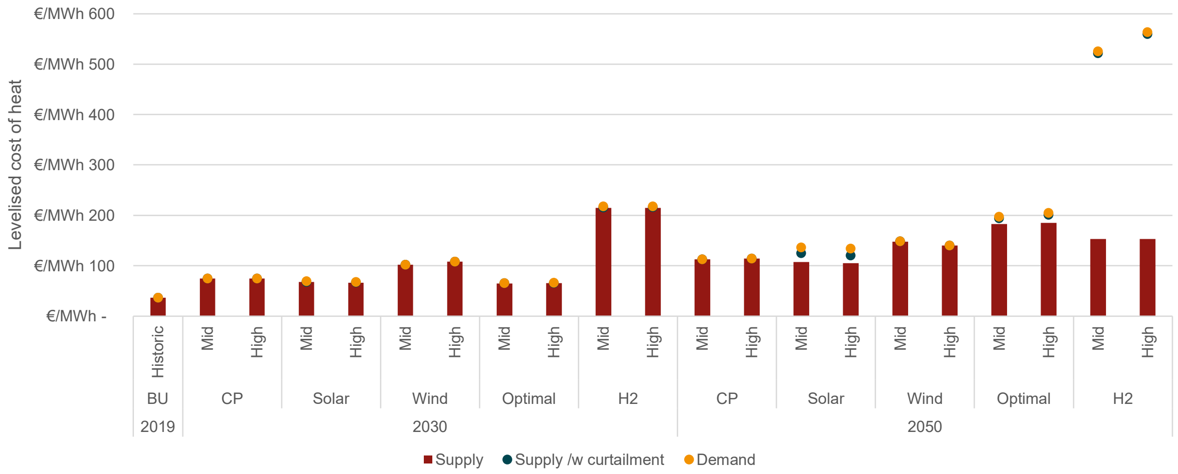


Figure 15: Levelized cost of heat for each scenario and development concept

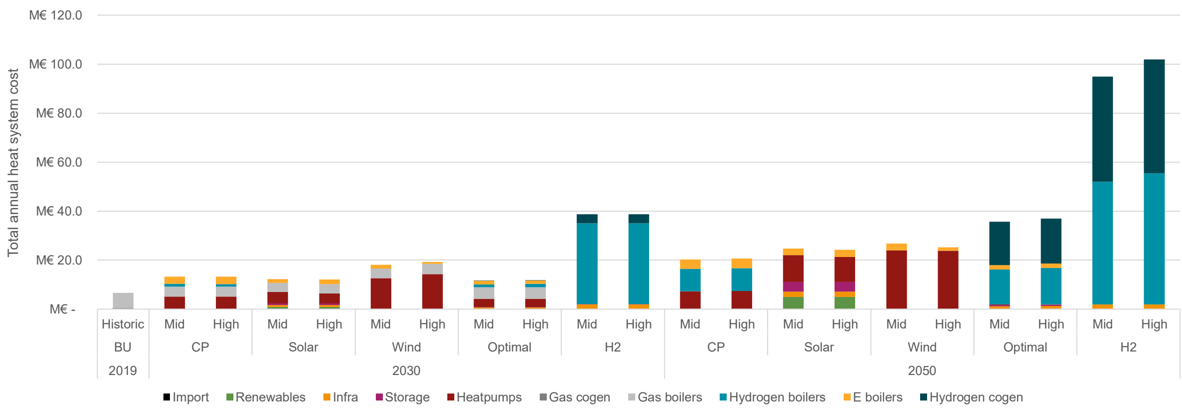


Figure 16: Breakdown of annual costs for heat production for each scenario and development concept

3.4.1.3 Airside

The airside activities modelled in Calliope can be subdivided in the towing of aircraft, ground power equipment and general service equipment. Figure 17 presents the amount of tow trucks and the maximum amount of aircraft for both WiBo and NaBo aircraft.

Calliope structurally under deploys hydrogen tow trucks, i.e. too few trucks for the maximum required according to the flight schedule. This is a numerical characteristic of cost optimization and the value of lost load; at some point deploying additional tow truck capacity which is used only once per year is more expensive than accepting that some load cannot be supplied. The model does not account for back up units. For E tows, overcapacity is deployed in 2030 resulting from a different trade-off. The results for the high scenario wind cases have been omitted, as the model was too constrained such that it was not possible to install sufficient tow trucks. This resulted in unacceptable quantities of unmet demand on one hand, and overly well utilized tow trucks resulting in too low LCOE values. The same holds for the optimal cases.

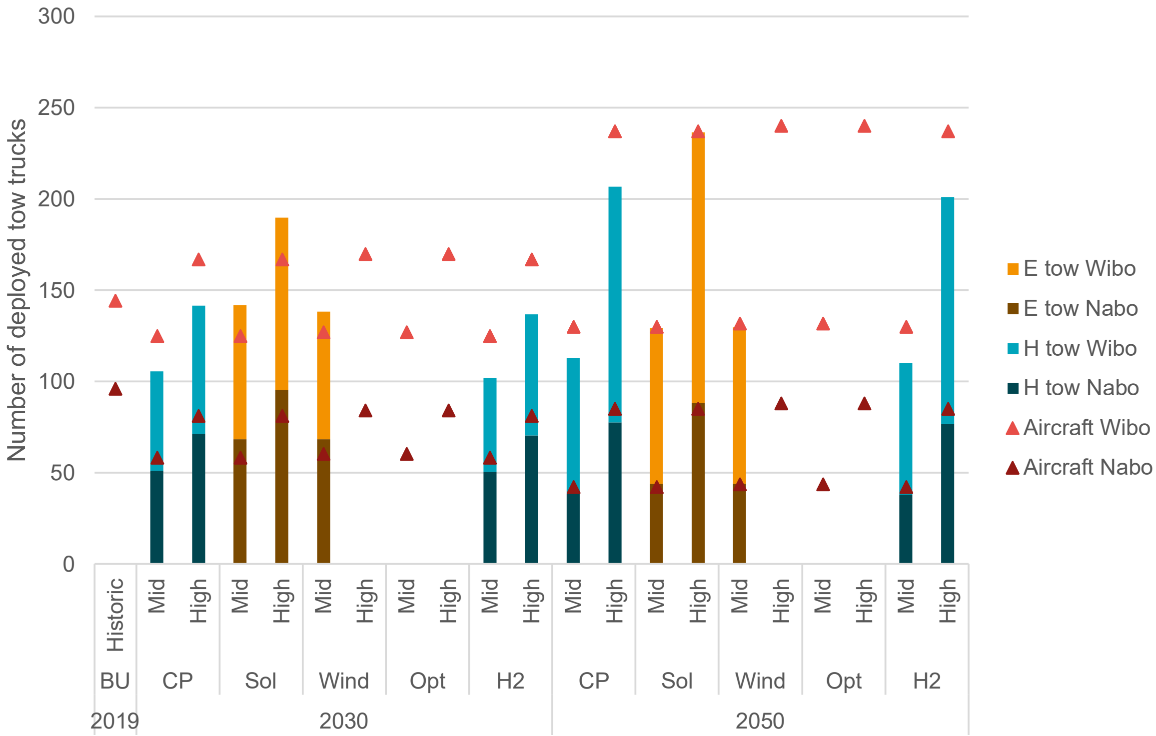


Figure 17: Breakdown of number of deployed tow truck for each scenario and development concept

Figure 18 presents the levelized cost for tow trucking in the different cases. Supply LCOE indicates all cost up to and including the tow truck, including CAPEX and OPEX of tow trucks and supporting infrastructure (chargers and hydrogen compression and fueling station), and the levelized cost of the energy carrier (hydrogen or electricity). Demand LCOE then shows the cost per unit of towing and reflects the efficiency at which the tow truck is operated. In this study, the costs for a hydrogen unit and a battery unit were assumed to be equal since cost data for hydrogen powered tow trucking was not available in literature. Hence, to reduce the effect of the cost assumption on the outcome, these costs were assumed equal. For E tows, the cost drivers are on one hand the higher energy efficiency and the potential to access low cost renewable electricity, and on the other hand the time required to charge the tow trucks, thereby possibly keeping them out of service for some time, and the need to store electricity if charging needs to be done at times that renewable electricity is not available. For hydrogen powered tows, the cost drivers are the relative low energy efficiency, and the continuous operation and hydrogen readily available form the grid on the other hand. Thus, this analysis basically compares the following cost drivers: total required energy to power the tow trucks, the cost at which this energy is available (electricity versus hydrogen, including infrastructure to supply this energy), and the number of tow trucks that need to be installed.

In the base case, the costs of the aircraft engines were ignored and the cost of kerosine is relatively low, leading to a relatively low supply LCOE. But jet engines running at low load is incredibly inefficient, assumed to be 10%, pushing up the cost of towing with a factor of 10.

In this analysis, any form of alternative towing has the potential to greatly reduce cost. For 2030, the towing was found to be most cost effective when E tows were combined with a grid connection. This way, the benefits of smart charging was utilized, while keeping the number of required tow trucks at a minimum. This is a typical display of high CAPEX, low OPEX solution. The towing costs of E tows for the wind case is on par with those of H2 tows in the CP and H2 cases. This picture changes significantly for 2050, where the assumed drop in hydrogen price becomes decisive.

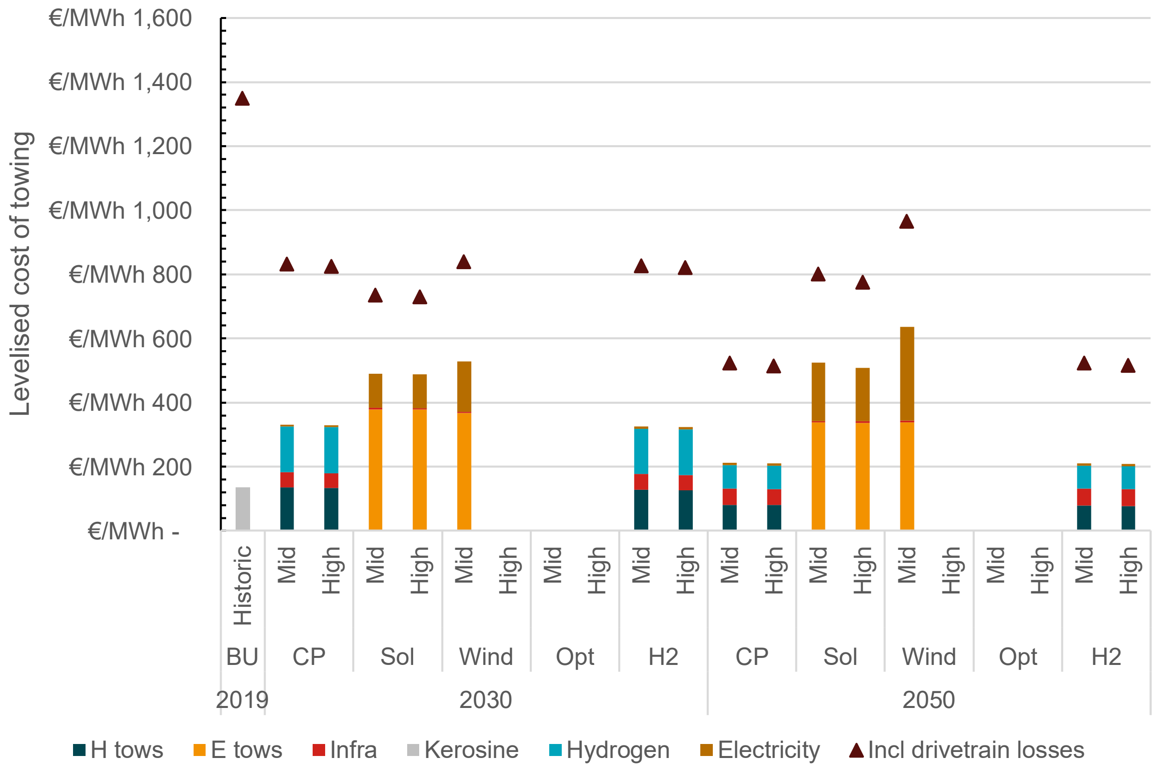


Figure 18: Breakdown of levelized cost of energetic cost for towing for each scenario and development concept

Figure 19 shows the levelized cost for ground power for the various development concepts. The hydrogen case employs hydrogen mobile units everywhere; Current policy employs H2 mobile units at remote locations only. Similarly, solar allows a combination of fixed units at A - H gates and E-GPUs at the R and S platforms, whilst the wind case only allows E-GPUs.

The cost for electricity procurement includes storage at utility level. It should be noted that flexibility of electricity supply in the current policy and solar cases is mostly supplied by the grid. Some cases show a slight drop in cost for the high scenarios with regards to the mid scenario. This is the result of the relative size of freight transportation at Schiphol: energy demand of passenger aircraft, handled at gates with fixed GPUs, is much higher for the high scenarios, diminishing the impact of the cost necessary to supply ground power at the R and S platforms where freight is handled.

The effect of these choices is clear. For both 2030 and 2050 the lowest cost is achieved by deploying fixed ground power units in combination with near baseload electricity supply from the grid (current policy and solar cases). Electricity storage in E-GPUs instead of utility scale RF battery systems seems unwise. Note that remote buffer and parking locations such as U platform was not included. Hydrogen GPUs seems like an unwise choice, except for remote locations in 2050. The option of installing fixed units at remote locations should be further investigated.

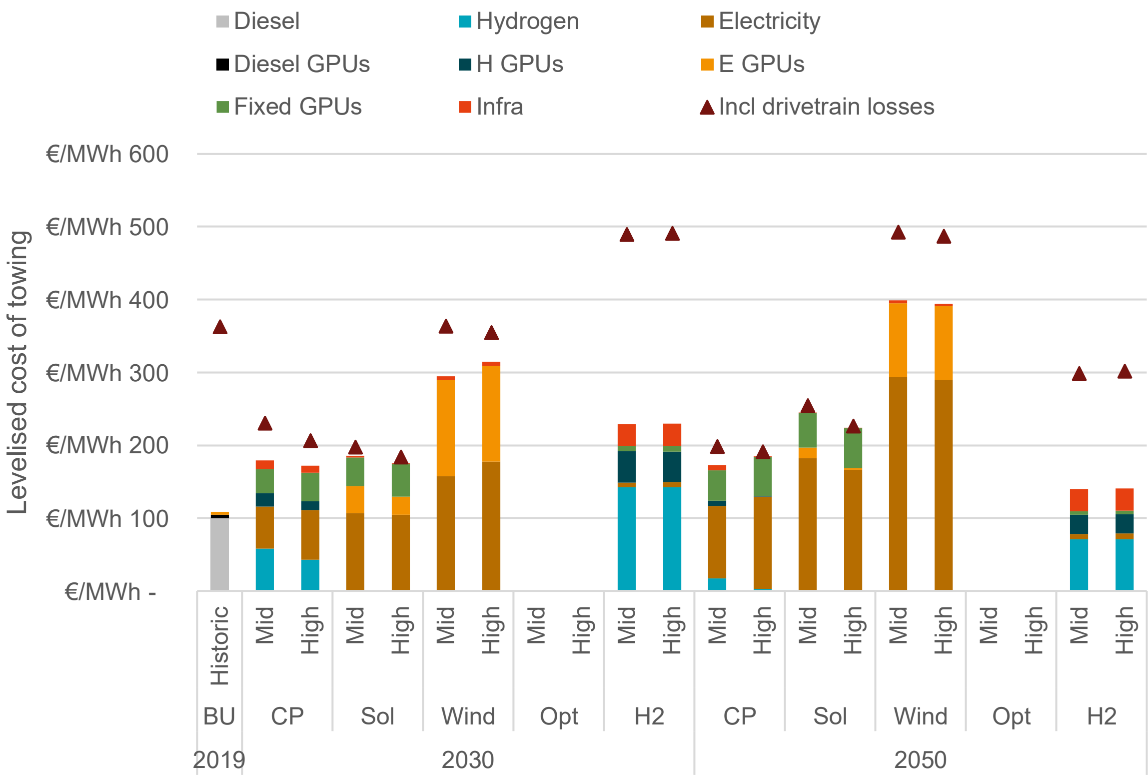


Figure 19: Breakdown of levelized cost of ground power for each scenario and development concept

3.4.1.4 Storage

Error! Reference source not found. shows the installed capacity for storage systems in the various development concepts. In the case of electricity storage, the model almost solely install redox flow storage systems. The installed storage capacity of thermal storage systems is significantly higher. The installed capacity for both the solar and wind case is due to the imposed constraints of the development concept. In the optimal case, the model only deploys heat storage and no electricity storage.

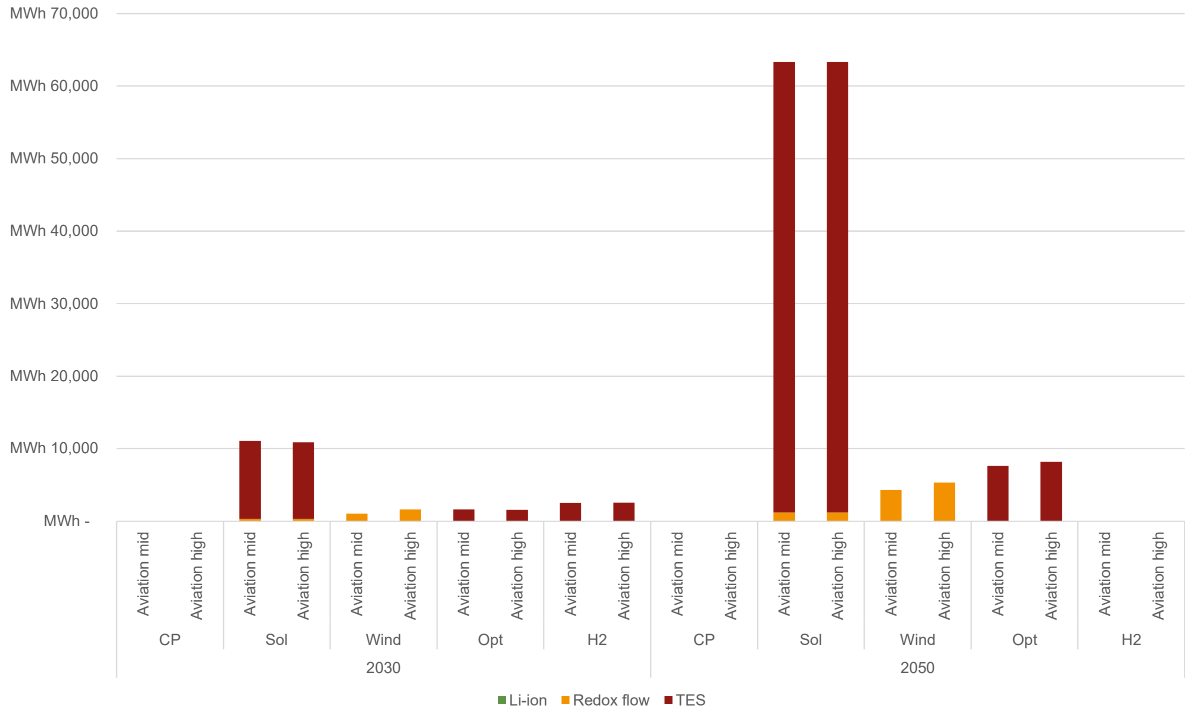


Figure 20: Breakdown of the installed storage capacity per asset type for each scenario and development concept

The levelized cost of storage is shown inFigure 21, electricity storage is quite costly due to the CAPEX cost and the lower than ideal amount of cycles as shown Figure 22.

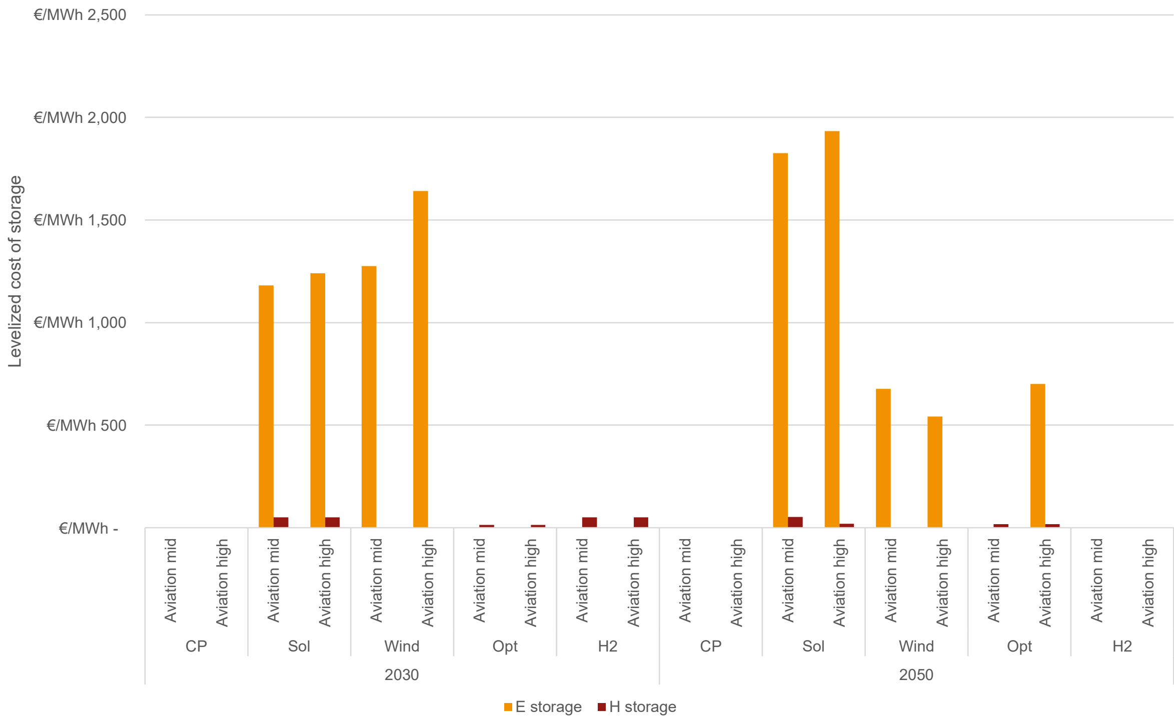


Figure 21: Levelized cost of storage for each scenario and development concept

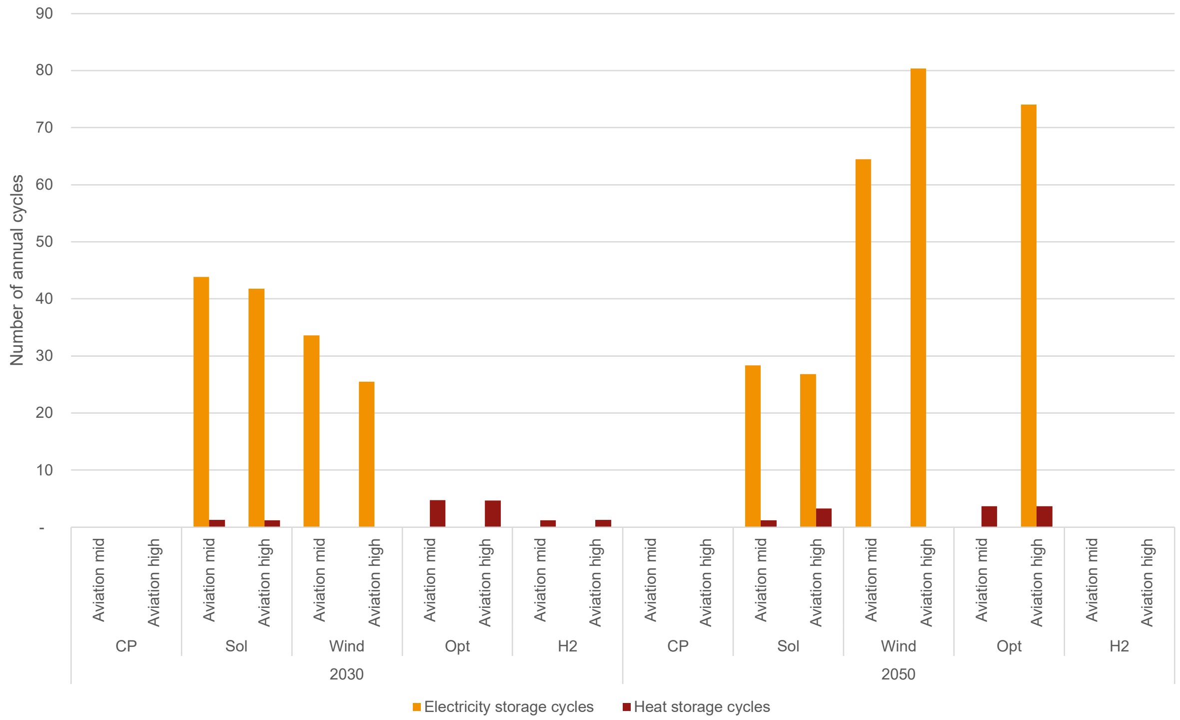


Figure 22: The number of cycles per storage type for each scenario and development concept

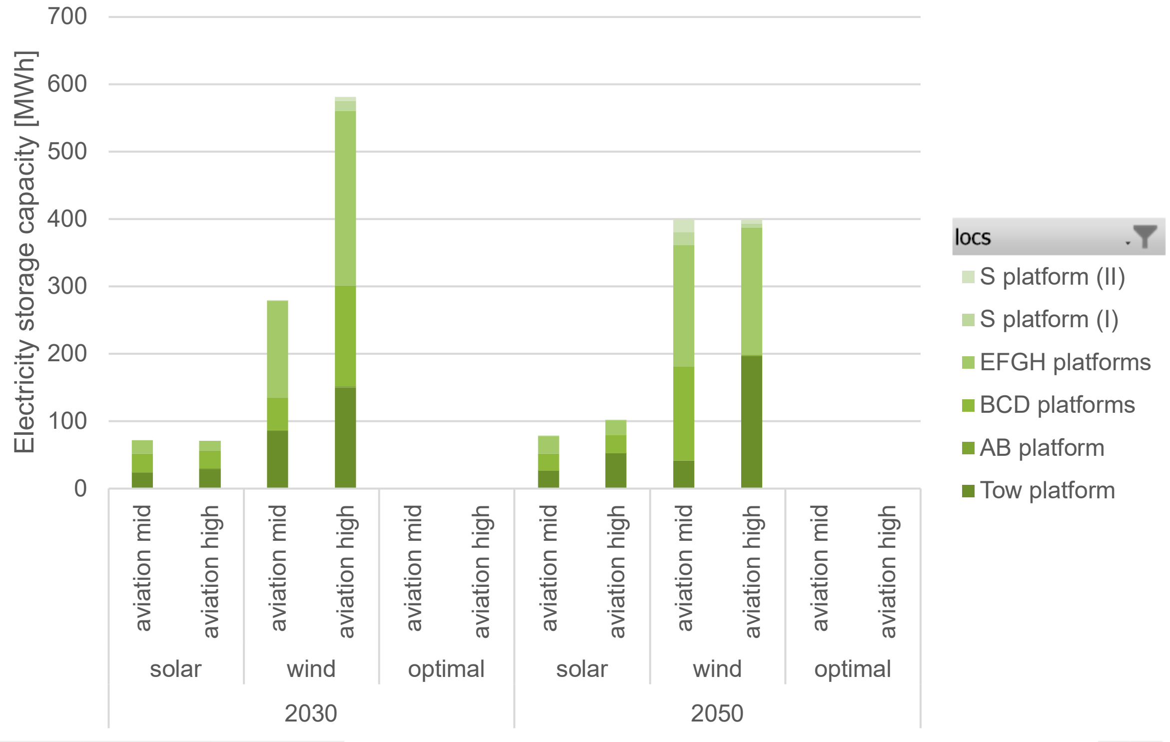


Figure 23: Breakdown of the installed storage capacity per location for each scenario and development concept

Figure 23 shows the installed electricity storage capacity at the demand side. In the wind development concept the storage capacity is fixed to the demand side whereas in the solar case the storage capacity deployment is not tied to a specific location

3.4.1.5 Infrastructure

The power distance for infrastructure is shown in Figure 24. The power distance is the installed capacity multiplied by the distance. The highest power distance is in the wind case because the connection to the wind park is explicitly modelled.

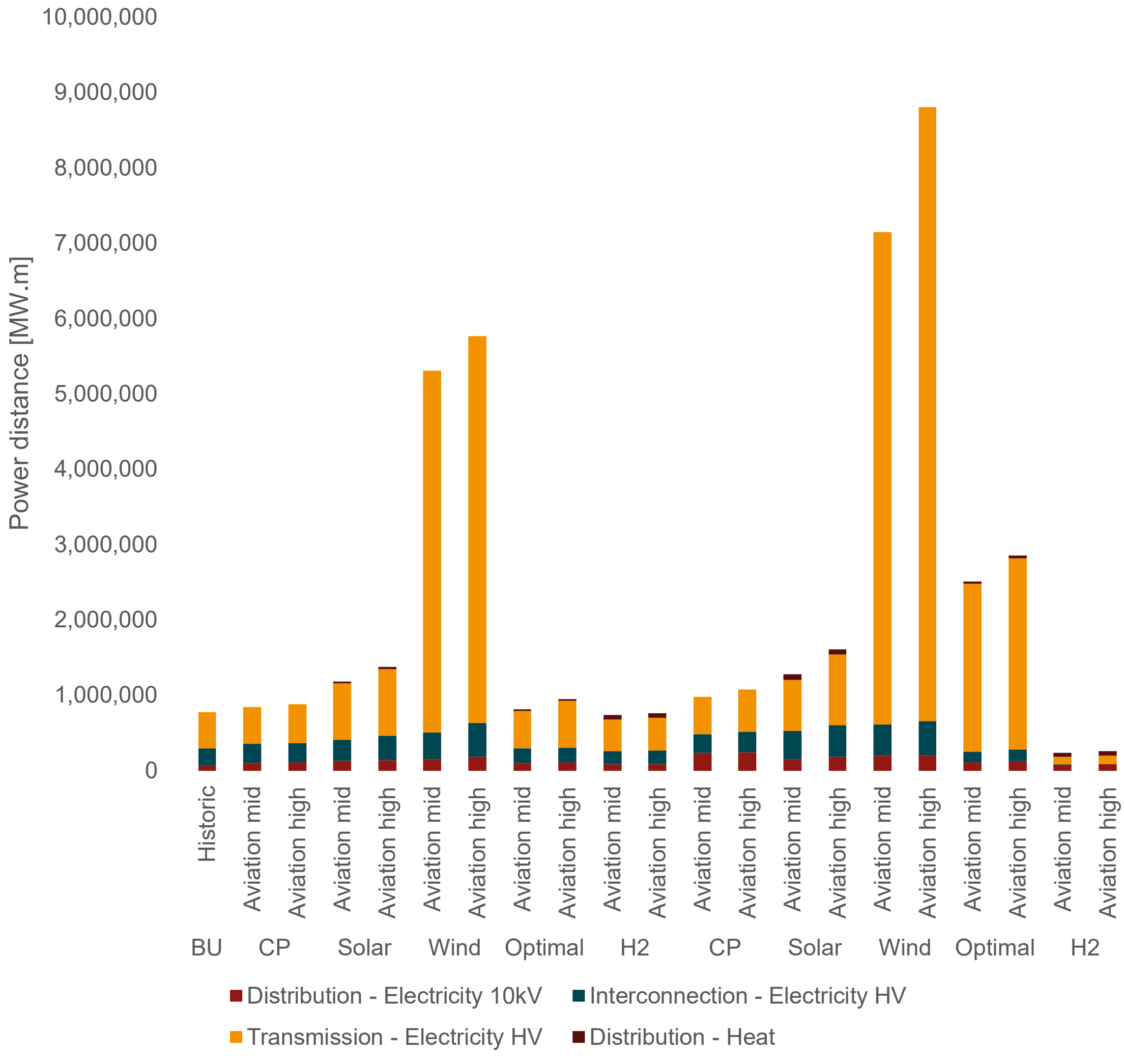


Figure 24: Breakdown of total power distance for infrastructure for each scenario and development concept

3.4.2 Evaluation of modelling results

The result section shows the output of the different model runs. In this section, an interpretation of the results will be given.

Aviation scenario impact on energy system configuration is limited

Even in extreme growth scenarios, impact on system configuration is limited. This can be considered a positive outcome, as this reduces the risks related to the uncertainty in aviation on Schiphol to the decisions that need to be made related to the Schiphol energy system. Impact of aviation demand decrease could not be analysed due to a lack of data, so no conclusions can be drawn for this case. Similarly, data for development of the built environment was not available for future years, so impact of building stock that matches the aviation growth scenarios as well as impact of new building designs was not incorporated. Most notably, effects of energy efficiency and insulation of buildings resulting in decreased heat demand, increased cooling demand and suitability for heat pumps are missing.

Subsidies and cost of capital

In this study, no subsidies were considered. Furthermore for the cost of capital, an interest rate of 10% was assumed. This interest rate has a great impact on the results presented in this chapter and may be a conservative estimation. Loan schemes with lower interest rate may significantly reduce the cost of capital, and as a result improve the levelized cost of any capital intensive asset, such as electric tow trucks, heat pumps, PV systems, wind turbines, energy infrastructure and storage systems, and as a result the price of electricity. Assets that can be assumed to be independent of the interest rate are boilers of any type, gas engines and the price of hydrogen. Table 8 shows the impact of the assumption of interest rate on the cost of capital. This effect should be considered when interpreting the results.

Table 8: Annual cost of capital [%/year] for different interest rates and different economic lifetimes.

Economic lifetime (years)	5	7	10	15	20	25	30	50
Interest rate 10%	26.38%	20.54%	16.27%	13.15%	11.75%	11.02%	10.61%	10.09%
Interest rate 3.5%	22.15%	16.35%	12.02%	8.68%	7.04%	6.07%	5.44%	4.26%
CAPEX reduction	16%	20%	26%	34%	40%	45%	49%	58%

This table shows the impact of more favourable loan conditions for in investment. In this study, all interest rates were assumed to be 10%. For an asset with an economic lifetime of 30 years, cost of capital can be reduced by 49% when an interest rate of 3.5% can be applied instead.

Deployment of tow trucks is a no-regret with most impact in abating Schiphol CO2 emissions while saving money

- Kerosine use for aircraft taxiing is both biggest source of emissions and largest cost component
- Deployment of tow trucks can potentially abate an estimated 250 kton of emissions per year, even more when considering growth of aviation, while saving tens of millions of euros each year. While these costs currently belong to airline operators, this unlocks a business case for KLM Equipment Services and Schiphol to deploy tow trucks and the required energy infrastructure, offering a service to airline operators that saves them in fuel costs. This result includes all investments in tow trucks, chargers or hydrogen infrastructure and production or procurement of electricity or hydrogen. This analysis excludes the economic wear of aircraft engines, as well as adjustments to the airport infrastructure such as tarmac, parking lots of the tow trucks. To the authors, it is unknown what the airside infrastructural implications are. Assessment of single engine taxiing with sustainable aviation fuel (SAF), which increases the efficiency of the engines and uses a carbon-neutral fuel, was not included in the analysis for 2030 as carbon-neutral SAFs will not be available at sufficient volumes to provide a realistic alternative.
- For 2030 E tows were found to be most economic, while hydrogen tow trucks also have significant economic and environmental benefits. This study assumes hydrogen available to Schiphol through the gas grid for 150 euro/MWh by 2030, but it is highly uncertain if this is realistic. The latest Hydrogen market development is facing significant challenges today, Despite the challenges in rolling out the electric infrastructure, it seems that the required charger capacity could fit in the existing infrastructure plans of Schiphol.
- For 2050, results show that costs of hydrogen and electric tow trucks are on par with one another, although it must be added that while for hydrogen a price decrease of 50% was assumed for 2050 with respect to 2030, capital costs for both the electricity and charging infrastructure and the tow trucks were kept constant. This means it is likely that the costs for electric tow trucks are overestimated, which would put electric tow trucks at an advantage.

Fixed power and preconditioned air units where possible, mobile units where necessary

- In this study, ground power and preconditioned air were found to have near baseload profiles, also at night time, especially so when the increasing number of flights are more evenly distributed over the day.
- Battery units have a charge time that naturally restricts their capacity factor, making them unsuited for a baseload type of demand
- Fixed units turned out to be much more economic in every case, recommended to investigate whether fixed units are also possible at remote locations

- No reason to believe that storage functionality of EGPUs have value compared to grid solutions because of their high CAPEX
- Phase out of diesel GPUs mostly interesting for improvement of air quality, impact on CO2 emission is limited
- Only consider as temporary measure to speed up phase out of diesel units and further reduce APU use
- Take whatever measure is possible to avoid APU usage

Smart charging of airside equipment has limited potential at Schiphol

Smart charging is a great way of avoiding the need for stationary storage solutions, as electricity production from renewable sources can be directly consumed by the vehicle battery. This unlocks the low levelized cost of electricity from renewables sources.

We observe that the potential for smart charging with airside assets is very limited. This seems to be a direct effect of the high unit cost of airside battery vehicles, in particular E tows and E GPUs, which discourages creating flexibility by having spare units. The consequence is that electric tow trucks follow the day-night cycle typical for aircraft taxi activity: in operation during the day, parked and charging at night. Whenever an E tow is not used, it should be parked at a charging station so that charging can take place during the day as much as possible, but charging of tow trucks at night cannot be avoided from an economical and logistical perspective.

With respect to ground power, installation of fixed power units was found to be a superior solution for gate positions in each scenario. When mobile GPUs were used, for example at remote locations, the load profile of docked aircraft was observed to be of a near baseload nature, so generally GPUs are charged as soon as they are empty and put to use as soon as they are charged to alleviate other, almost depleted GPUs. This * limits the potential of smart charging.

Smart charging of passenger EVs was not included in this scope. Still, it is expected that EV smart charging, in particular of EVS on long term and employee parking lots, has great potential at Schiphol because of the predictability of the availability of EVs and the scale of cars. It is strongly recommended to look further into this topic to see how PV at Schiphol can be utilized better.

Direct market access unlocks lower electricity prices

Currently Schiphol has a flat rate contract for its electricity. On one hand, this removes any financial incentive for Schiphol to coordinate its energy use as the price is always the same. On the other hand, Schiphol its energy supplier needs to mitigate any risks through the flat rate. Simulations show, in particular the Current Policy 2030 cases, that direct access to the electricity market can already reduce cost of electricity significantly with 20 €/MWh on average. There are two aspects to consider. Firstly, the simulations represent a system with a smart control system that can optimally trade-off electricity procurement and load shifting. Secondly, Schiphol will need to carry the financial risk of extraordinary high electricity prices. But considering the existing backup power generators of Schiphol, this does not necessarily have to be an issue as Schiphol would be able to provide part of its own electricity at times that prices are very high. Also, this would unlock the potential electricity storage that flexible procurement

Electricity storage is still very expensive

Energy storage was investigated by including storage capacity as a prerequisite for deployment of renewable electricity production in the wind and solar cases. The model had the choice between deploying lithium-ion systems and redox flow systems. The power capacity and the storage capacity of the redox flow system can be scaled separately, while for lithium-ion this ratio was fixed at a factor of 4 MWh/MW. Under the current cost assumptions the model always went for a redox flow system. The impact of storage cost on levelized electricity cost is shown in Figure 25

Please be aware that also in terms of storage limitations apply. Firstly, only li-ion and vanadium redox flow battery systems were considered, while upcoming technologies like Na-ion, which are based on the much cheaper electrolyte Na, were not. Also, learning curve cost reductions were not considered.

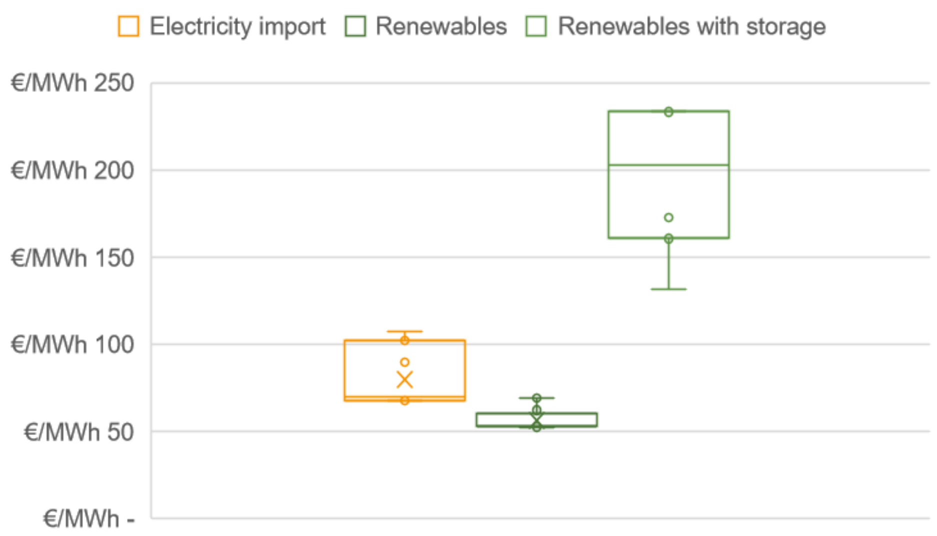


Figure 25: Levelized cost of electricity for all 17 cases that were simulated, where each dot represents a single case.

Not every case had access to renewables or storage assets, so fewer points may be shown for these categories. What is shown here is that in almost every case the levelized cost of electricity from the market is higher than of electricity from a renewable source (both wind and solar, excluding curtailment). This is only a valid comparison when all renewable electricity is consumed directly. Whenever storage assets are considered as part of the investments of the renewable system, costs increase dramatically.

Contracting offshore wind

- Actual wind power without Certificates of Origin
- LCOE of 58 euro/MWh, with much higher capacity factor than solar, very effective to reduce electricity costs
- Increasing requirements in tenders for offshore wind park developers to consider system integration, creating interest in partnership or PPAs
- From current results it is difficult to say what is optimal share of wind, but results suggest that at least 100 MW should fit in portfolio as well as in, providing more than 400 GWh renewable electricity without needing to expand interconnection capacity

Solar power can cut back effective demand of Schiphol, overproduction should be avoided

PV is a low cost source of electricity when used directly, however, it becomes very expensive when combined with batteries. Figure 26 shows the levelized cost of storage (LCOS) of batteries as simulated in this study for all cases with battery storage. The costs are determined by the fixed CAPEX and OPEX and their productivity as was realised in the simulation. This provides an improved estimation of the LCOS compared to the theoretical potential (also shown in the graph), which assumes maximum use of the battery system.

The developments in battery technology should be monitored to see if assumed CAPEX costs drop with at least a factor of two, which would put a PV system with a well designed battery storage system with a full cycle per day in the right cost range. For batteries with a realised productivity as calculated in the simulations, costs would need to drop by a factor of 10 – 40.

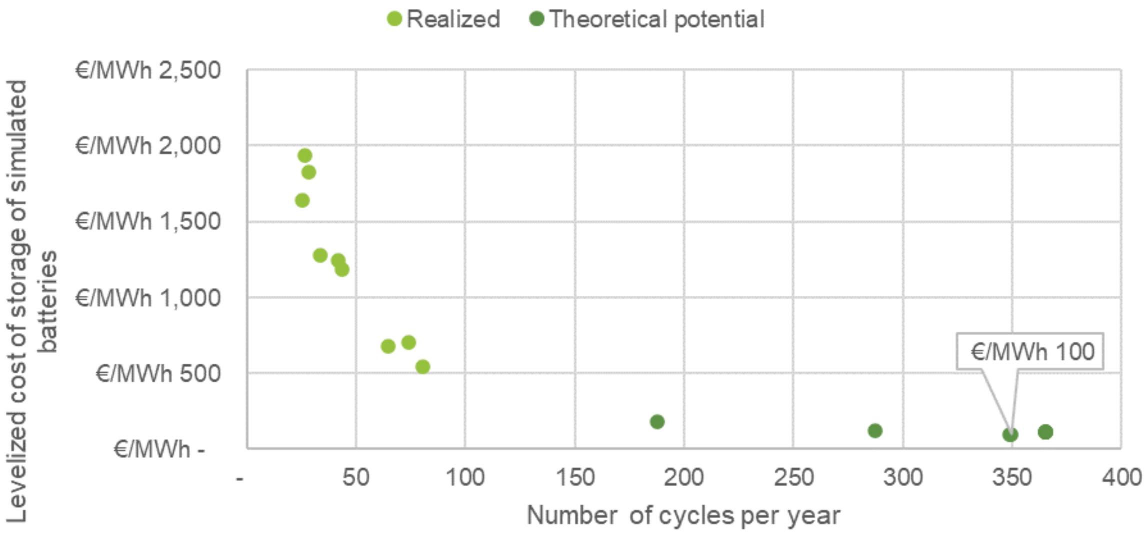
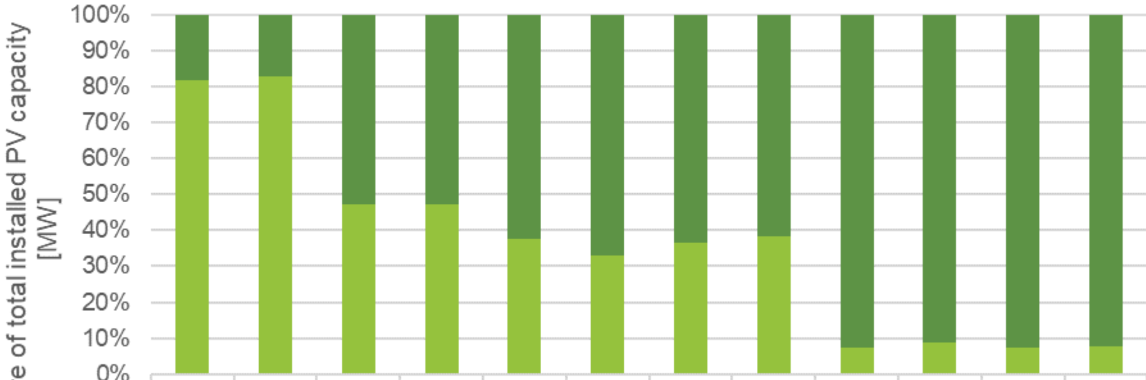


Figure 26: Levelized cost of storage of Vanadium Redox Flow battery systems versus the number of cycles as realized in the simulations and in theory, assuming maximum productivity of the battery system.

The variation in theoretical number of cycles is the result of the varying storage duration [MWh/MW]. For example, systems with a ratio of 24 can only achieve 180 cycles per year, as they require a full day to charge and a full day to discharge.

Rooftop PV should be used to reduce demand of buildings and maximize self-consumption, utilize natural simultaneity of day-night rhythm of PV and e.g. electricity use in offices and cooling, but avoid converting buildings into power plants, avoid increasing grid capacity for PV. The impact of alternative PV systems, such as vertical panels or North-West orientated systems not investigated



	Mid	High	Mid	High	Mid	High	Mid	High	Mid	High	Mid	High
	2030		2050		2030		2050		2030		2050	
	CP				Wind				Opt			
Field	3.8	3.6	105.8	105.8	13.1	14.1	63.3	61.6	90.0	89.6	199.6	221.2
Roof	17.2	17.4	94.2	94.2	7.9	6.9	36.7	38.4	7.1	8.7	16.2	18.6

Figure 27: Distribution of capacities between field and roof-mounted PV in the solutions that allowed optimization by the model.

Below the figure are the calculated values in units of MW. For the Current Policy cases, the optimal distribution is dependent on the year.

Autarchy is currently an economic utopia, interconnectivity of electricity remains important

From the analysis, there is no reason to believe that Schiphol can become energy-neutral, let alone autarchic (isolated from the national electricity grid). While autarchy was never a clearly formulated goal, there was the question as to what degree self-provision of energy for airside operations and buildings was possible. The amount of solar panels required to provide Schiphol with its energy would amount to GWs, with incredible amounts of storage to buffer all this energy, which is produced in only 10% of the time. When considering electricity market independence, reflected by the Wind and Hydrogen 2050 cases through contracted wind turbines or onsite electricity production from hydrogen, the results show that technically it is possible, but the system costs for electricity are driven up intensely compared to cases where interconnections remain part of the solution. This does not mean that smart energy hub solutions like storage and onsite production cannot reduce the dependency on the external grid.

Exceptions:

- When market independence is a strategic goal, storage is required;
- When storage is used for short term balancing purposes as a result of forecasting errors; in the current modelling exercise all demand was foreseeable. Electricity market prices can and will significantly increase when supply or demand are mismatched;
- When interconnection reinforcement is not possible for reasons other than economic ones, such as limitations at the DSO/TSO.

The planned interconnectivity capacity expansions is likely to accommodate full electrification with support of a smart control system

According to the DNV "Netstructuurplan" written in 2022 on behalf of Schiphol shows that as of 2026, at least 150 MW installed interconnection capacity should be available to Schiphol. As shown in the left graph in Figure 28 with calculated contract capacities, the results indicate that this should be sufficient to accommodate even heavy electrification on Schiphol. Please note that in the model contracted capacity were used, and that these values do not represent installed connection capacities, which may be higher. Also note that capacities for passenger EV charging infrastructure is not included.

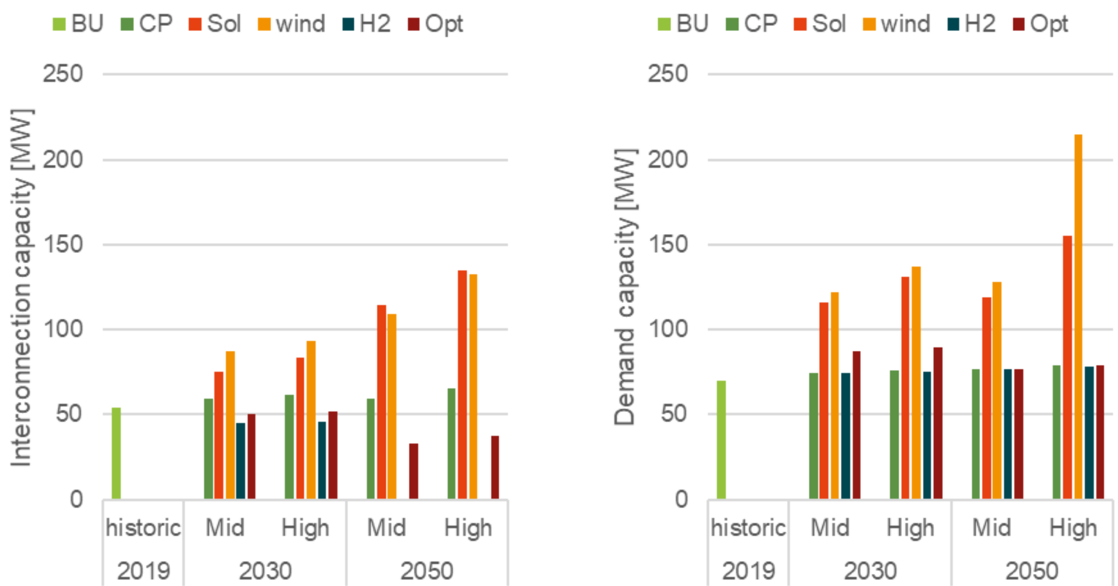


Figure 28: Cumulative contract capacities of electricity interconnection with TenneT/Alliander (left) and of end point consumers on Schiphol (buildings and airside charging stations, right figure).

in the right figure, the cumulative end point contract capacity is shown, which shows that the demand side capacity is structurally higher than the import capacity. This shows that interconnection capacity can be reduced in the following two ways. Firstly, many cases assume onsite power production capacity and storage which increases the self-consumption of electricity onsite and reduces the need of import capacity. The ultimate example of this is the 2050 hydrogen case where all electricity is produced onsite. Secondly, the optimization model assumes a smart control system which can coordinate the operations of all assets within the system. This unlocks optimal use of the electricity grid as the control system can balance supply and demand locally, avoiding net congestion and uncontrolled peak loads, both in supply and demand.

Some aspects of the modelling approach may provide limitations when putting the modelled configurations into practice. Firstly, the model assumes perfect foresight, meaning that there is no error in its forecasting of supply and demand. In practice, forecasting error requires redundancy to deal with unexpectedly high supply or demand. This can be addressed by increasing the grid capacities of the system with a safety margin, as well as installing back up power supply. On the supply side, Schiphol can consider introducing a limit on the connection capacity for PV installations up to 30%-50% of the installed capacity of the PV system. This prevents intense peak loads of PV systems, while limiting the loss of the annual renewable energy production.

Secondly, the modelling approach ignores any organisational boundaries, assuming as much control over the heat pumps of third party consumers as over batteries installed on airside. In practice, this can be implemented by setting up a local electricity market. Some examples of local markets can already be found in the Netherlands where consumers try to deal with limited grid capacity by coordinating their activities with one another. Similarly, this could align the interests of all stakeholders of the Schiphol electricity and gas grid. The legal and organisational aspects of such a market were not investigated in this study.

Based on these results, a better picture should be obtained of the required physical connection capacities of the different electrification options.

Electrification of heat has most economic potential

After decades of having access to cheap natural gas, building owners should expect that the costs of heat increase when decarbonization is pursued. Whether through electrification of the production of heat through heat pumps and e-boilers or by replacement of gas with hydrogen, the levelized cost increases. This does not mean that all options are equally good or bad, though. The calculated costs for all cases are compared in Figure 29. These values reflect the total cost of ownership of an asset, including CAPEX, OPEX, economic lifetime, interest rate and fuel cost as applicable for each case. The dotted line (--) indicates the reference value for 2019 based on a gas boiler.

When interpreting these results, the following limitations of the modelling approach should be considered. Firstly, no insulation measures were considered that may be required for the deployment of heat pumps for existing buildings, nor were improved efficiency standards considered for new buildings. This means costs for deployment of heat pumps may be underestimated. Secondly, cooling demand was not included, neither existing cooling demand nor additional cooling demand resulting from insulation of existing buildings. Insulation reduces total energy demand and shifts the heating/cooling load more towards the summer periods, improving the simultaneity of building energy demand and PV/ST production and improving the economics of heat pumps. Thirdly, the demand profiles for space heating were based on historic profiles assuming gas boiler heating systems. This means these profiles show high volatility in demand, which adversely affect the performance of heat pumps and benefits that of boilers (both E and hydrogen fuelled). Finally, no technology learning curves were assumed for any of the assets, while hydrogen price reductions were assumed. Learning curves reflect the reduction of fixed costs of a technology over time as a result of innovations, economies of scale, improvements in the supply chain etc. As a result, especially the cost of CAPEX heavy equipment like heat pumps can be expected to be overestimated in this work.

The lowest cost of heat was found in the 2019 reference case, with natural gas at 25 €/MWh and a boiler efficiency of 85%. For 2030, replacing gas with hydrogen dramatically increases this cost, with a factor 4-6 and heavily dependent on the price of hydrogen. Electrification through a combination of heat pumps and E boilers is the most economic and energy efficient option. Heat pumps supply the baseload heat demand very efficiently, while E boilers is a relatively cheap solution for peak demand and flexibility. Note that this is deemed a conservative cost estimation as historic heat demand profiles were used based gas boiler installations. These are less suitable for heat pumps, so by considering a more baseload heat supply profile, more of the heat could be supplied with heat pumps, reducing the LCOE even further than presented here.

Towards 2050, the increasing cost of electricity drives up the cost of electrification, improving the economic potential of solar thermal power with storage and heat grids. This may be a signal to further investigate how solar thermal power could be integrated in the existing heat infrastructure, as it simultaneously may alleviate the load put on the electricity grid by PV. Hydrogen is still not considered a good decarbonization strategy for heat, although the assumed reduction in hydrogen price reduces the gap somewhat.

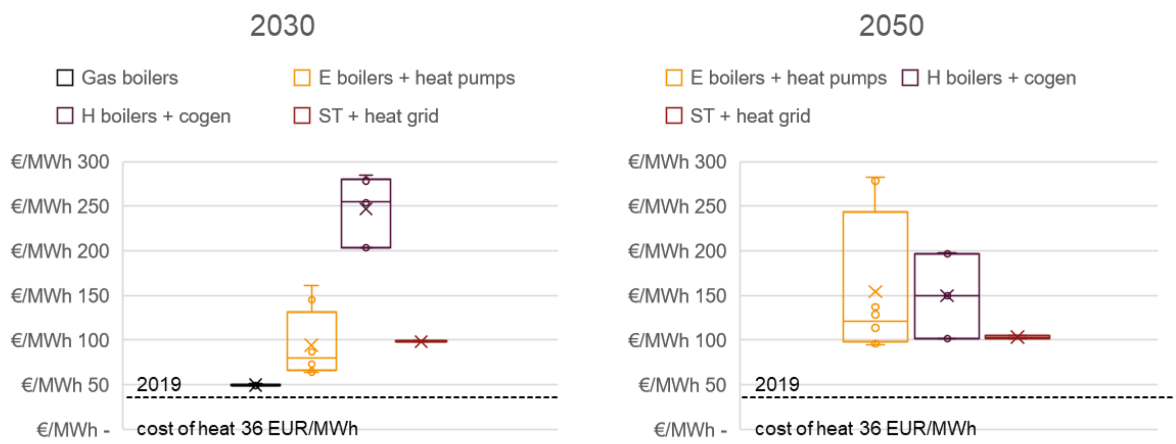


Figure 29: Box plots with a comparison of the levelized cost of production of gas boilers, E boilers combined with heat pumps, hydrogen (H) cogeneration combined with H boilers and Solar Thermal collectors with pit thermal energy storage and heat grids for all simulated cases.

To showcase the positive economic impact of the high energy efficiency of heat pumps, the levelized cost of production of heat pumps combined with E boilers in shown in the graph below Figure 30. Because heat pumps are so much more CAPEX intensive than boilers (both E and hydrogen), it can be challenging to get a feel for the cost reduction effect during its economic lifetime. In the graph, the LCOH of heat pumps with E boilers are shown against the levelized cost of electricity that was found for each case. Naturally, with higher costs of electricity, the cost of heat increases as well. What is more is that heat pumps perform so efficiently that, despite their high CAPEX, they perform economically equal or better a free of charge E boiler for which only the electricity bill needs to be paid. In other words, the cost savings on electricity during its lifetime make up for the investment cost up front.

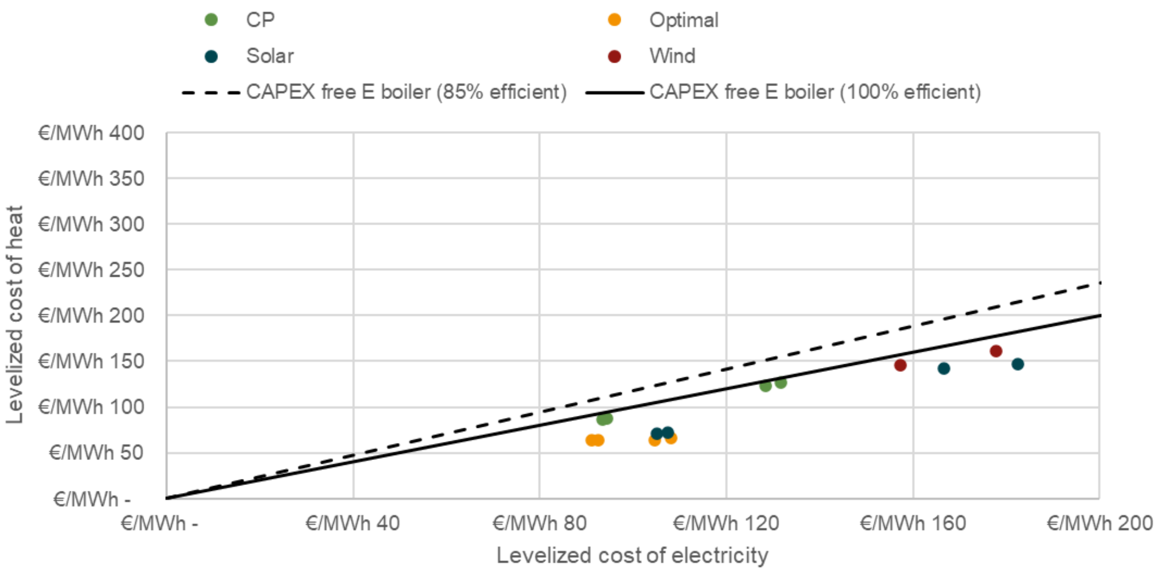


Figure 30: Levelized costs of energy for electrification of heat for all cases with heat pumps for all scenarios (mid/high and 2030/2050 – coloured markers) compared to the marginal cost of production of heat with e-boilers (lines).

Heat storage is cheap

With around 56 euro/MWh per unit of stored energy for seasonal storage and as low as 17 euro/MWh for monthly storage, pit thermal energy storage was found to be a very affordable way of storage compared to electricity. Basically being a large body of water, this technology only works at scale and requires a heat grid to provide buildings with access. In the model, a fixed ratio between the power and the storage capacity was assumed. An even lower cost of storage may be achieved when the design is further optimized. Pit thermal energy storage should be combined with solar thermal power to provide a cost competitive alternative to e.g. heat pumps or combined with hydrogen cogeneration to buffer the heat and get more value out of the cogeneration.

Hydrogen-based cogeneration could be an option for backup

From the results, cogeneration with hydrogen as main source of supply of electricity and heat was shown to be a very expensive pathway. In the 2050 optimal case, where import of electricity was not allowed, some cogeneration was deployed as a cheaper alternative to back-up battery packs. Cogeneration in combination with adsorption cooling was not included. This may result in better use for the heat produced in summer periods, as the heat produced in summer is too expensive to be stored for winter. Using this heat for cooling may improve the business case. Still, it is not expected that this makes hydrogen fired cogeneration a competitive technology as primary source of energy.

For flexibility and back up, cogeneration, in particular gas engines, can be more valuable. Technologies with a low CAPEX compared to their fuel costs are well suited for backup applications, as their LCOE will be dominated by this CAPEX cost. In the case that hydrogen infrastructure will not be developed at Schiphol, SAF could be considered as well. The value of flexibility was not quantified in this work and should be studied in more detail.

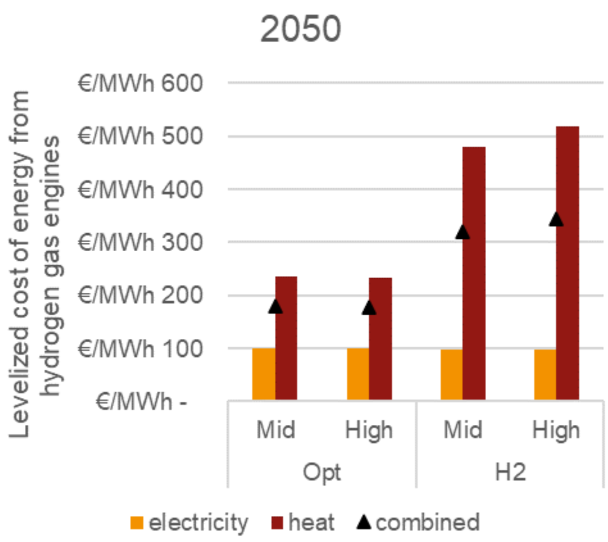


Figure 31: Levelized cost of energy of cogenerated heat and electricity from hydrogen fired engines in 2050.

Electricity is the main energy product, so the LCOE of heat varies based on the effective use of this heat. In the hydrogen cases, much of the heat needs to be vented into the atmosphere as there is no direct use for the heat, driving up the LCOE. The combined value indicates the average between the two and quantifies the LCOE when costs would be split over the two carriers equally.

3.4.3 Robust smart energy hub concept(s)

Some general design considerations for a renewable energy system.

- Diversification is key. One returning element that can be observed in well-designed systems is diversification of technologies, in particular when technologies with a high efficiency/low OPEX and high CAPEX but are mixed with low efficiency/high OPEX and low CAPEX technologies. Ideally, high CAPEX technologies are run consistently, maximizing the output to justify their high investment costs. Low CAPEX, high OPEX technologies are great for flexibility purposes, as keeping the asset on standby is not so financially impactful as for high CAPEX assets. Typically, these assets also have better response times.
-

	High efficiency	**High flexibility**
Heat production	Heat pump	E-boiler
Electricity production	Combined-Cycle gas turbine	Open cycle gas turbine
Mobility	Battery EVs	Fuel cell EVs

- Not every kW of installed renewable capacity can be utilized. As renewables have intermittent, weather dependent profiles, the output of an installation varies over time: sometimes the output is closer to zero, sometimes closer to 100%, but mostly somewhere in between. When designing a system for 100% of the capacity of renewables, the system becomes expensive very quickly. For example, for a 1 MW_p solar installation, it is better to design the distribution grid and any storage assets at less than 100%, for example at around 0.7 MW electrical capacity, or combine the renewable asset with other assets that have peak loads at different times of the day (called cable pooling). This will save up to several tenths of % of CAPEX, which would have only be used a small number of hours in the year.
- Levelized cost of electricity from the market is higher than of electricity from a renewable source (both wind and solar, excluding curtailment). This is only a valid comparison when all renewable electricity is consumed directly. Whenever storage assets are considered as part of the investments of the renewable system, costs increase dramatically. This is in particular the case with PV, which is a low cost source of electricity when used directly, however, it becomes very expensive when it needs to be combined with battery storage.

3.5 Conclusion

Schiphol Group's ambition is to operate the world's most sustainable, high-quality airports. Schiphol Group wants its operations to be zero-emissions and zero-waste by 2030 and to function as an energy-positive and fully circular organisation by 2050. Equally important, Schiphol Group will continue to play a leadership role in driving sustainability across the aviation sector, aiming for net-zero carbon emissions aviation by 2050.

The current study explores possible pathways to achieve these goals.

The methodology applied in this study is called the ‘solution space method’. The method deploys scenario’s (sets of unknown parameters external to the decision makers) and technology concepts (sets of technological measures that may be chosen by the decision makers). The Solution Space is a matrix with the scenarios on one axis and the concepts on the other axis. This method is very well suitable to align with all the stakeholders on a high level on the scenarios and concepts that will be involved in the study. Due to this selection, the number of options that need to be studied is reduced. As a consequence, this is not an optimization study that delivers the best possible concept. Not every technology combination is studied, and the level of detail is limited. The method supports robust decision making at the strategic level.

As the future is unknown, an explorative scenario approach was used to address the uncertainty in demand for aviation and the building stock at Schiphol. The scenarios involved in the study are airport business scenarios based on the AEOLUS aviation reference forecast for the development of aviation in the Netherlands. The reference forecast differ in terms of the development of the amount of air traffic towards 20230 and 2050. This chapter does not attempt to provide detailed predictions of the future, nor provides answers to questions as “how much PV should Schiphol have deployed by 2050?”. Certainly, 2030 is approaching rapidly and decisions need to be made soon in order to achieve the goals set for this year. But the world is changing rapidly.

Four development concepts have been used. Namely, current policy (CP), ‘solar’, ‘wind’ and ‘hydrogen’. Current policy aims to capture the current direction but is in no way reflective of Schiphol Groups current strategy. Table 2.5 presents the technological solutions available to the different development concepts for electricity generation.

For current policy 21 MWp of solar will be deployed in 2030 either on rooftop or in-field. Towards 2050 this will be increased to 200 MWp. The remaining electricity demand will be procured on the market. The ‘solar’ development concept reflects an increased deployment of solar PV. The ‘wind’ development concept reflects a wider portfolio where offshore wind is more directly contracted. The ‘hydrogen’ development concepts does not deploy any renewables and instead relies on a hydrogen-fired CHP and the grid for electricity demand.

Table 9 (repeated) : Selected electricity generation technologies for each development concept in different scenarios, = technology unavailable, = technology available

	Current Policy		Solar		Wind		Hydrogen	
Technology	2030	2050	2030	2050	2030	2050	2030	2050

Utility-scale solar PV	21 MWp	200 MWp	75 MWp	300 MWp	21 MWp	100 MWp		
Rooftop solar PV								
Offshore Wind					100 MW	> 200 MW		
Hydrogen CHP							100 MW	300 MW
Import gridmix	150 MW	150 MW	150 MW	100 MW	50 MW	0 MW	50 MW	0 MW

For each development concept shown in Table 2.5, a set of heat generation assets and airside technology assets are selected. Every development concept consists therefore of a combination of a higher power of a specific sustainable power supply together with a set of assets that matches that specific supply best.

A number of important conclusions from the study are:

- A ‘low hanging fruit’ that scores very well in every scenario is electrification of the heating demand.
- Application of solar PV is cost effective up to the level that the green electricity that is produced can be utilized instantly and preferably also locally at the building where it is produced. Utilizing excess PV at a later time quickly reduces the cost-effectiveness.
- Electrification of Tow Trucks scores very good in terms of emission reduction and cost effectiveness but is complicated to implement because it requires grid reinforcement and charging infrastructure. The total number of trucks on the airport increases significantly, and the logistics of returning trucks from the airstrip is a complicating factor.
- The same conclusion applies to electrification of FPU, APU and GPU’s.
- The most cost-effective way to solve the intermittency issue and the supply-demand issue of intermittent green power is at the level of the grid operator and not on the airport itself. However, this is only a valid choice when the grid operator takes care of this issue in a timely and costly manner. Deferring this task to the grid operator creates an uncertainty in achieving the airport's sustainability goals and a strategic dependence on the grid operator. This conclusion holds for both an external power grid and a hydrogen supply grid. The airport needs to make a strategic decision for dependency on third parties at a potentially lower cost, or achieving their goals independently of third parties at a higher cost.

- Grid reinforcement costs are a relatively small amount of total cost. Saving on grid infrastructure may be counterproductive. It is recommended to assess how much 'head space' (spare power) is available on the grid, and to prioritize electrification options e.g. electrification of buildings vs electrification of GPU's or Tow trucks.

The limitations of the current study are:

- Electrification of e.g. Tow Trucks and GPUs is considered only from a CO_2 reduction perspective. Reduction of other emissions e.g. dust particles, NOx and diesel fumes might be important and increase the relative priority of these electrification options.
- Smart charging of EV's and other e-mobility is left out of scope.
- The cooling demand of the buildings is left out of scope. A low-cost cooling distribution grid connecting ATES to buildings to avoid electrical chillers may lower the electricity demand of the buildings.
- A scenario with lower air traffic is not considered.
- Scenarios are based on the Aeolus model and a projection from SNBV for the number of buildings; these scenarios are not coupled and not necessarily consistent.
- A historic flight schedule is used, and scaled linearly to the future, without replanning the flight schedules; optimisation of flight schedules is possible and will lower the peak demand. For buildings a historic energy demand profile is used; this is not yet an optimised profile for heat pumps.
- Any exposure on the imbalance market is not included in the results.
- The calculation of the electricity price is based on assumptions for the electricity mix in 2050.

4 Torino Airport – scenario study and system design concepts

4.1 Methodology

The ambition for a net-zero energy system will require radical changes in the way energy is sourced and consumed at Torino Airport. A well-pondered plan will be fundamental to avoid regrettable investments, but informed planning is hindered by the complexities inherent to renewable-based systems and by the unavoidable uncertainties surrounding the long-term evolution of energy and technology markets. Inside Annex 1 a more detailed general overview of the context in which the airport is located together with an overall framework of the carbon footprint and ambitions is summarized. The following sections describe instead how such complexities were dealt with to support the development of a *robust* energy strategy for the airport.

4.1.1 Methodological framework used for the scenario analysis

The breadth of the energy transition will embrace all the aspects of the energy system of the airport, from the way energy is source or produced on-site to that in which this energy is consumed to satisfy the countless services offered by the airport to passengers and airlines. In order for the analysis to deliver an integrated development plan, all the relevant aspects must be properly accounted for.

The extent of such a modelling activity introduces several layers of complexity with respect to traditional methodologies employed by industries for energy planning. Three main complexities which can be early identified are:

- A wide pool of innovative technologies and solutions must be scrutinised, and their impact must be evaluated at the system level, taking in account of their interactions, especially in the view of a fully integrated energy hub.
- The extension of the timeframe of the energy planning activity is unprecedented. The need of planning over several decades is a relatively new trend, prompted by the worries around climate change and the related burgeoning of net-zero commitments. Traditional analysis methods, often focused on a shorter timeframe (single-year or few years analysis), could fall short in delivering insights on the progressive evolution of the energy system.
- Finally, a longer timeframe also entails broader uncertainties, in particular concerning the evolution of the energy and technology markets. Although the quantification of these uncertainties can be cumbersome, the representation of potentially different futures is fundamental for the definition of a *robust* energy system.

The last point of the list is often addressed by businesses through a *scenario analysis* [4, 5, 6]. It is worth spending some words to provide a proper definition of *scenario*, as intended in this work. As shown in Figure 1, the decision-making process is influenced by a number of factors affecting different elements of the energy system: from the decarbonisation objectives set by the airport itself to the trends in energy and technology markets. Some of these factors can be defined as *micro*, as they fall within the area of influence of the airport, whereas *macro*-factors are largely not influenced by the airport but, in turn, can play a major role in influencing the airport's decision. Briefly put, *micro* factors can be controlled as part of the airport's development strategy, while *macro* factors are uncontrollable and thus are a major source of uncertainty.

In the methodological framework adopted for this analysis, a *scenario* is defined as a coordinated set of assumptions concerning the evolution of the above-mentioned factors. Aim of a scenario is to *describe* a future in which the airport will have to take decisions about the configuration of its energy system.

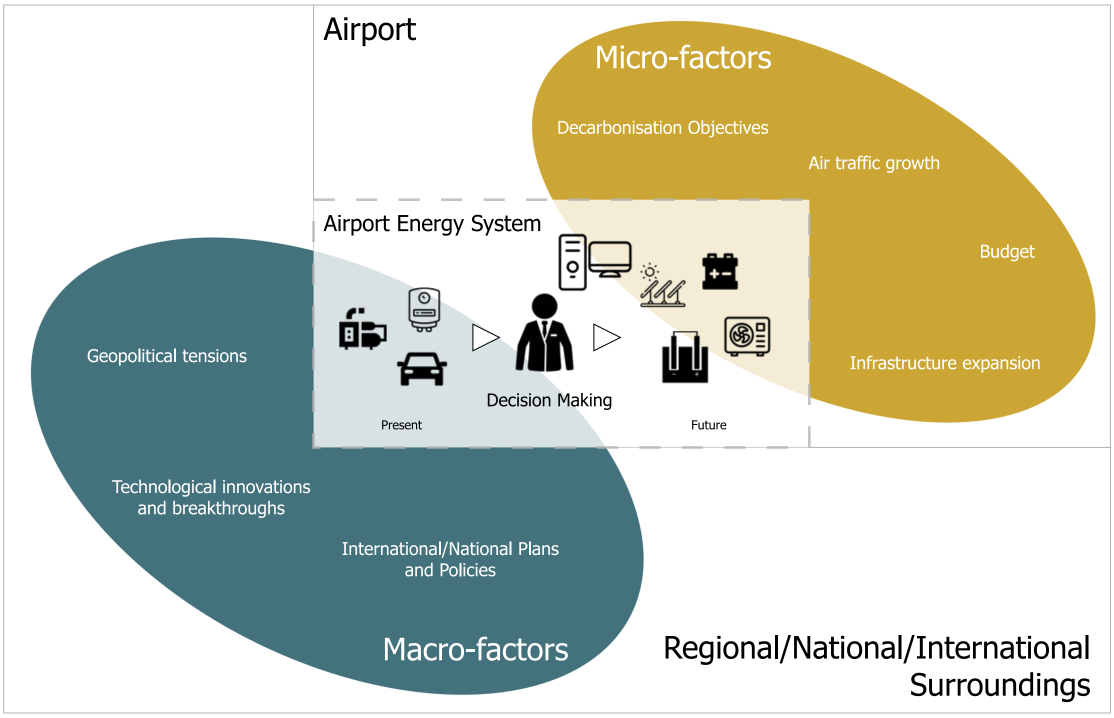


Figure 1 - Micro- and macro- scenario factors affecting the decision-making process of the airport.

The methodological framework adopted for this analysis, outlined in Figure 2 aims at addressing the complexities listed above through a scenario study. The analysis revolves around a techno-economic model of the energy system of the airport. This model provides an integrated mathematical description of the physics and economics of the present energy system, as well as of the alternative technologies which could come into play in the future.

The model embeds simplified mechanisms of the decision-making process, properly calibrated on the specific case of Torino Airport. Based on an optimization methodology, and building on the present assets and on the pool of alternative technologies provided, the model determines the least-cost configuration of the system satisfying the economic and environmental objectives set by the airport. The model, whose rationale is better described in section 4.1.2, fully addresses the list of complexities discussed above. It creates an integrated framework for the assessment at the system level of a large number of alternative solutions, evaluating the economic, technical and environmental aspects. Moreover, it is worth stressing that the assessment of the model is not limited to a snapshot in the future. The analysis is based on a multi-year approach, determining the optimal development pathway of the airport over the whole modelled horizon.

The main model acts as a computer-based energy planner, determining which solutions to invest in, the timing of the investment, the decommissioning of old technologies, and computing the energy balances and cash flows related to a configuration of the system. Such comprehensive modelling can provide important insights to the real planning activity, but it requires a significant effort in providing the input data, of which a comprehensive list is provided in section 4.2.

The methodology followed for the definition and use of the of the main airport model leans on four building blocks (Figure 2) the description of the current airport energy system, culminating with the realisation of a base airport model; the expansion of the energy system to include a pool of potential innovative technologies; the design of future scenarios and the exploration of the optimal development strategies and, finally, the assessment of the risks through the exploration of alternative future scenarios. This last step will not be part of this deliverable, and will be realised in a later stage of the TULIPS project.

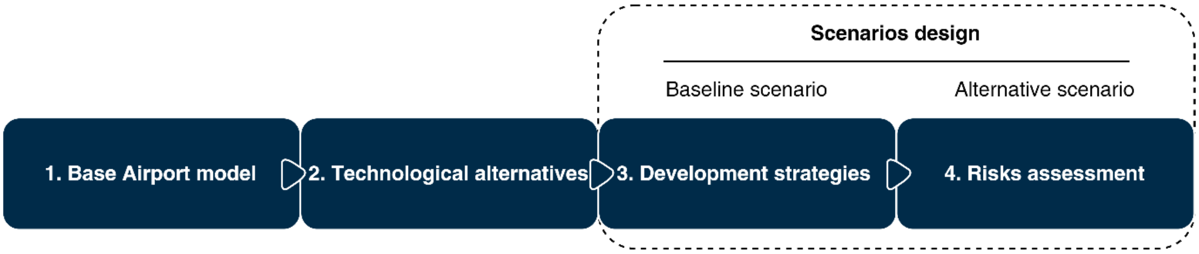


Figure 2 - Outline of the methodology adopted to study the optimal development pathway of the energy system of Torino Airport.

The first step of the methodology envisages the description of the current energy assets, consumption and infrastructure of the airport. The aim of this stage of the analysis is to get a comprehensive picture of the present structure of the airport energy system, its historical evolution and its relationship with the regional surroundings. This step is fundamental in order identify the main sources of energy consumption and emissions and consequently draw the boundaries of the study. Moreover, the analysis allows to spot the element of the systems for which there is room for improvement. The results of the first stage of the methodology are conveyed in a base airport model, able to reproduce the physical an economic flows of the current airport energy system.

Based on the identification of the airport's needs identified in the first step, a set of alternative solutions can be derived. The pool of potentially alternative technologies is derived from an assessment of the market of established and emerging technologies, appositely selected based on the peculiarities of the airport's site. The selected pool of technologies is then added on top of the base airport model, defining the set of alternatives which could be adopted to reach the desired targets.

The last two steps of the model involve the design of future scenarios. In the third step, a baseline scenario is defined for the *macro/uncontrollable* factors of the energy system and the investment optimisation model is used to derive the optimal development pathways of the airport under alternative airport strategies (or *micro/controllable* factors). In this study, two main strategical dimensions were selected for the analysis: the *Technology* and the *Ambition* dimensions.

The first dimension, *Technology*, expresses the will of the airport to pursue the development of its energy system counting on specific technology, restricting the initial pool. For example, one strategy could foresee the adoption of electrification measures alone, whereas another possibility would be to rely primarily on hydrogen-based technologies. This dimension allows to compare the advantages and disadvantages of different technological pathways. The second dimension, *Ambition*, regards the extent of the decarbonisation effort of the airport. The investment optimisation model is used to derive insights on the measures needed to deal with decarbonisation targets of growing ambition, investigating the additional costs and changes in the optimal system configuration implied. Combining the two scenario dimensions can also provide insights on the suitability of certain technological pathways to deliver more ambitious targets.

The last step of the methodology concerns the evaluation of model uncertainties through the investigation of alternative scenarios for *uncontrollable* elements. As stressed above, the main source of uncertainties when planning in the long-term is the necessity to make arbitrary assumptions on the development of elements of the local, national and international energy system surrounding the airport. The *optimality* of the development pathways identified in the previous step is therefore limited to the validity of the underlying assumptions defining the evolution of the airport's surroundings in the baseline scenario. In other words, each development pathway identified by the model as *optimal* could be *suboptimal* under a different future scenario.

In order to evaluate the risks associated with the choice of a specific development pathway, a set of alternative future scenarios (depicting, for instance, different energy and technology price trajectories) were designed. The performance of selected development pathways in each of these alternative scenarios will be evaluated in a later stage of the TULIPS project, assessing the risks to incur into additional costs and emissions.

4.1.2 Models and other tooling

The implementation of the methodology described in the previous section relied on a series of modelling activities, involving different tools. Lying at the core of the modelling activity is the well-established *Open Source energy MOdelling SYStem* (**OSeMOSYS**) framework [7], appositely expanded in order to reflect the peculiarities of the airport. OSeMOSYS belongs to the wide family of Energy System Optimization Models (ESOM). A common trait of all ESOM is the use of mathematical programming[8] to determine the *optimal* energy system configuration which satisfies the given technical, economic and environmental constraints. Typically, “optimality” is defined as an economic objective, most often as the minimization of Total System Discounted Costs (TSDC), although other criteria can be taken into account [8]. Due to their ability to handle complex decision-making processes, ESOM are frequently employed in the field of energy planning and policy exploration at various system scales [9, 10]. An in-depth description of the specific features of OSeMOSYS, together with a list of its input and output parameters, is provided in [7].

Beside the main OSeMOSYS model, several ancillary models were employed to build the necessary inputs. The variety of the models employed reflect the need to consider different aspects, both technical and economic, of the energy system. For this reason, they range from models describing the physical behaviour of technologies (like photovoltaic plants, fuel cell and storage) to simplified representations of the energy markets (such as the national utility grid, hydrogen and biomethane market). A non-exhaustive representation of the modelling chain is illustrated in Figure 3.

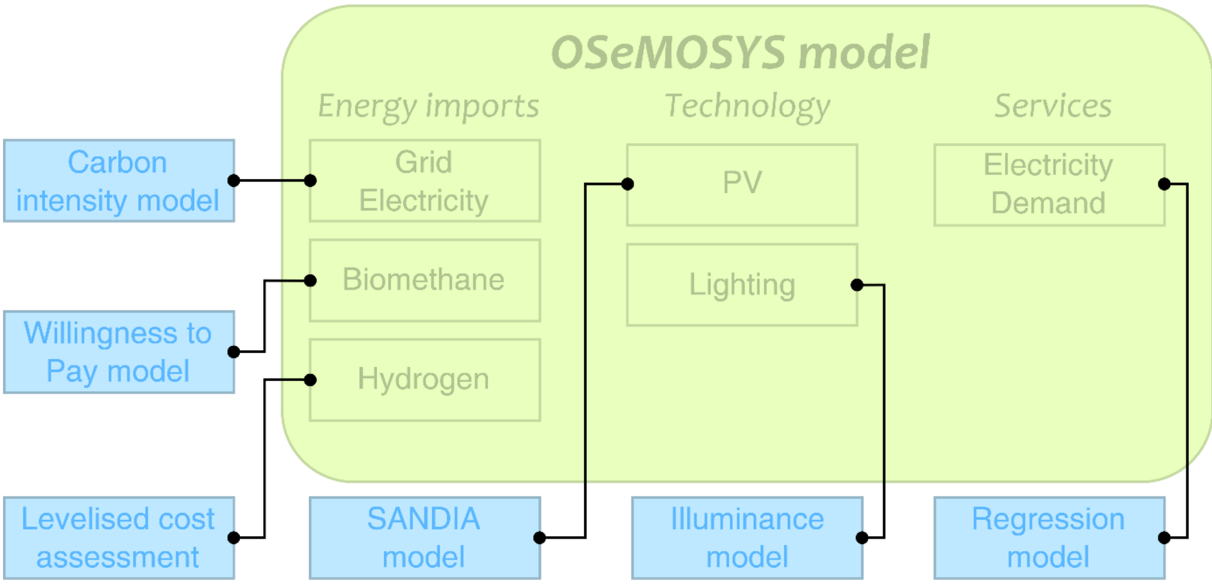


Figure 3 - Unexhaustive illustration of the modelling chain employed for the study.

[8] *Mathematical programming* comprises a range of techniques aimed at building models for planning purposes. In the words of Prof. H. Paul Williams: “*The common feature that mathematical programming models have is that they all involve optimization. We wish to maximize something or minimize something. The quantity that we wish to maximize or minimize is known as an objective function*” [64].

4.2 Scenarios and solution pathways

4.2.1 Energy demand of the airport

A more detailed description of the airport's energy system together with a focus on the evolution of consumptions during the last years can be found in Annex 1, below a more strict focus on the repartition of the energy demand is shown.

In 2019, the airport consumed nearly 17 GWh of electricity (Figure 4). More than a half of the overall consumption is associated to internal and external lighting (about 30%) and for cooling/heating and ventilation loads (30%). Another relevant share is related to the companies that conduct their activities within the airport borders (Tenants), such as bars, restaurants and shops (12%).

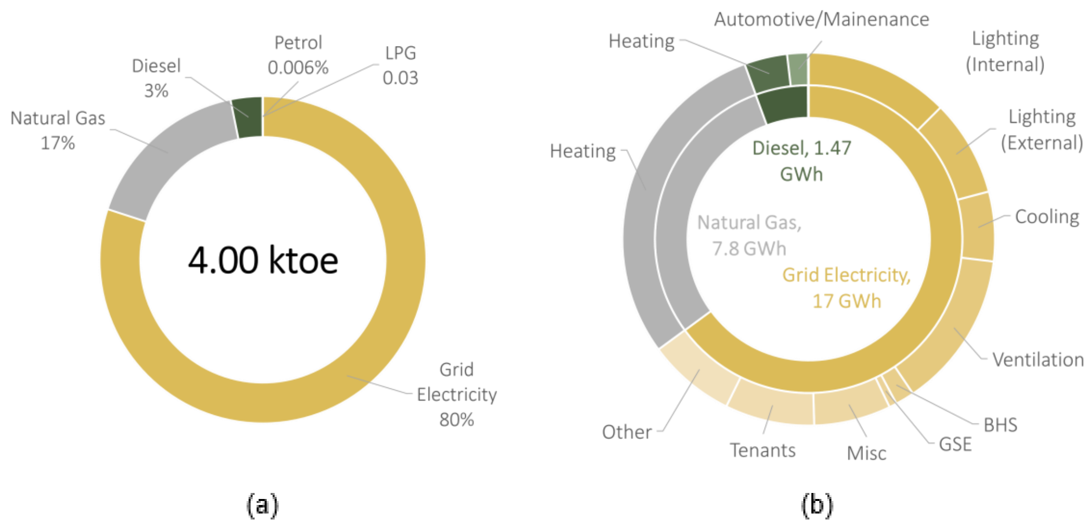


Figure 4 - Primary energy consumption (a) and final use of energy vectors (b) of the airport in 2019. Primary energy consumption was computed using the conversion factors provided by ARERA.

The majority of the purchased natural gas was used for the generation of hot water. Most of the diesel was burned for heating purposes, while a minor share served to fuel the airport cars and for operations both on land and airside.

Figure 5 illustrates the distribution of airport consumption through the year, for each energy vector. Driven by colder temperatures, the consumption of natural gas and diesel is higher in winter, especially in January. The peak electricity consumption is reached in the summer months, when the cooling system is switched on, implying a high dependency of energy demand on weather conditions. The lowest energy demand is registered in May, when both the heating and cooling systems are off.

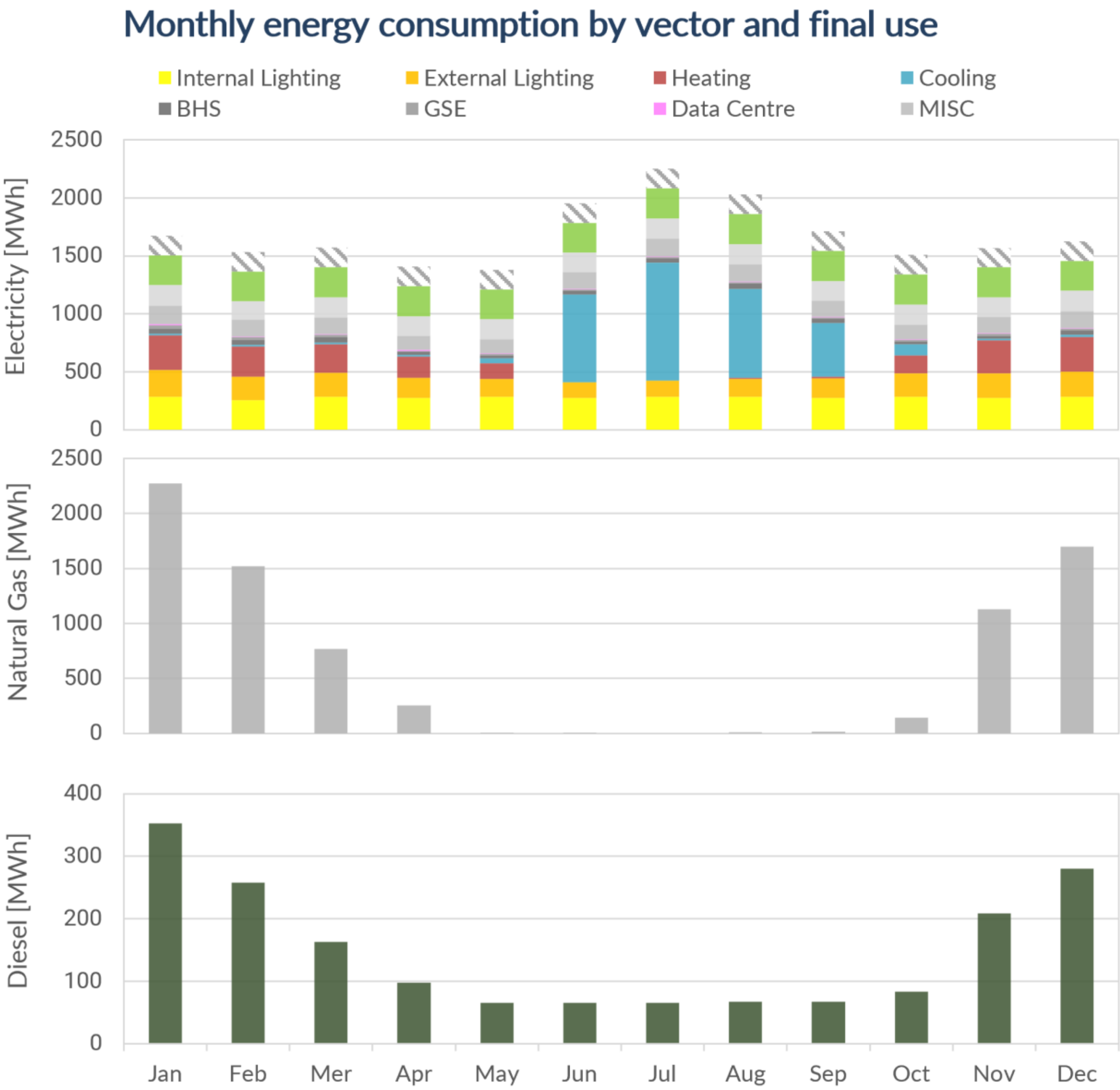


Figure 5 - Distribution of airport consumption through the year (2019 data).

4.2.2 Energy system key performance indicators

The KPIs taken into consideration to evaluate the configurations provided by the model are:

1) Energy balance for specific years of interest (2030, 2040, 2050) and thus the consumption breakdown according to the different categories of use;
2) Primary energy supply for specific years of interest (2030, 2040, 2050) subdivided into the different energy vectors available;
3) Installed capacities of technologies and storages in specific years of interest (2030, 2040, 2050) and internal energy configuration proposed by the model to meet the airport energy demand;
4) Share of renewable generation in final energy demand for specific years of interest (2030, 2040, 2050) to check not only the impact of the specific measures implemented but also the

independency of the system from the national grid and the resilience to the possible energy prices fluctuations;

5) Annual emissions, broken down by emission source, for the whole modelled period.
6) Cash flows for the entire modelled period. Breakdown of cash flows by type (fixed costs, capital costs, etc.) and by energy vector/technology with analysis on the variation in the balance between the two.

4.2.3 Energy system scenarios

Modelling the evolution of an energy system for several decades into the future requires to make assumptions on the development of its activities and surroundings. These assumptions are necessarily arbitrary, due to the unpredictability of future events, in the long- as well as in the medium-term. To deliver a sound energy strategy, it is therefore important to consider both the evolution of key elements of the surrounding energy system, from energy and technology markets to the increase of air traffic, as well as the inherent uncertainties.

In order to explore the optimal development pathway of the airport, a *Baseline scenario*, depicting a likely evolution of the uncontrollable elements of the energy system (e.g., energy and technology price) was designed. This required to make assumptions on the evolution of a number of energy system elements, of which a non-exhaustive list is reported in Table 1 Key elements of the *Baseline scenario* are thoroughly described in the scenario description section.

Table 1 - List of the element of the energy system, and corresponding model parameters, for which a Baseline scenario *was designed.*

Domains	Influencing Factors	Model parameters
Aviation	# passengers	Electricity demand
Built environment	Airfield lighting	Electricity demand
Mobility	GSE electrification	Electricity demand
Energy	Electricity market	Electricity price
	Gas market	Gas price
	Diesel market	Diesel price
	Biomethane market	Biomethane price Biomethane availability
	H2 market and infrastructure	Availability H2 external supply H2 price
Technology	H2-related technology market	Fuel cell (CAPEX/OPEX/stack lifetime) Electrolyser (CAPEX/lifetime/efficiency)
	Li-ion Batteries market	Battery price
	PV market	PV (CAPEX)
	Grid decarbonisation	Grid carbon intensity

This *Baseline scenario* was fed to the model in order to derive optimal development pathways of the airport under different strategical choices. In particular, two strategic dimensions were explored: the *Technology* and the *Ambition* ones (Table 2). The *Technology* dimensions describes three technological pathways. In the *Electrification* pathway (*ELECTR*) only investments in PV and electrification measures are allowed (no hydrogen-related technologies. The purchase of biomethane is allowed only until 2045. Natural gas and diesel must be phased out by the same year. In the *Hydrogen* (*H2*) and *Hydrogen Import* (*H2_IMP*) scenarios there are no restriction on the choice of technologies, so that also hydrogen-related technologies can be selected by the model, if found convenient. The only difference between the two technological pathways is that in the *H2_IMP* scenario it is assumed that a supply of hydrogen will be available at the airport starting 2040.

Table 2 - Combination of Technology *and* Ambition *pathways simulated. The "X" indicates that the combination was simulated.*

	→ **Ambition**	**Ambitious**	**Accelerated**
↓ **Technology**		55% emissions reduction in 2030. 62% reduction in 2040. Net-zero in 2050.	55% emissions reduction in 2030. 90% reduction in 2040. Net-zero in 2050.
ELECTR	Only investment in PV and electrification measures allowed. Biomethane can be used until 2045. Phase out of diesel and natural gas by 2045.	X	X
H2	Possibility to invest in hydrogen-technologies. No external supply of hydrogen. Limited investment in batteries for electricity storage.	X	X
H2_IMP	Possibility to invest in hydrogen technologies. Availability of external hydrogen supply from 2040. Limited investment in batteries for electricity storage.	X	X

The *Ambition* dimension describes the commitment of the airport to decarbonise its energy system. Torino Airport has set ambitious decarbonisation targets for 2030 (-55%) ad 2050 (net-zero). However, these targets could be achieved following different decarbonisation trajectories. In order to understand how the speed of the decarbonisation would affect the overall system costs, two decarbonisation trajectories were explored: an *Ambitious* and an *Accelerated*. The two trajectories are represented in Figure 6.

The *Ambitious* target envisages a linear decarbonisation trajectory between 2030 and 2050, with an intermediate 78% reduction in 2040. The *Accelerated* scenario assumes that a 90% reduction of emissions will be reached already in 2040. It is noted that a small amount (3%) of residual emissions is allowed in 2050, mainly to avoid to over-constrain the optimisation model and allow the use of renewable fuels with residual lifecycle emissions, e.g., HVO for maintenance vehicles.

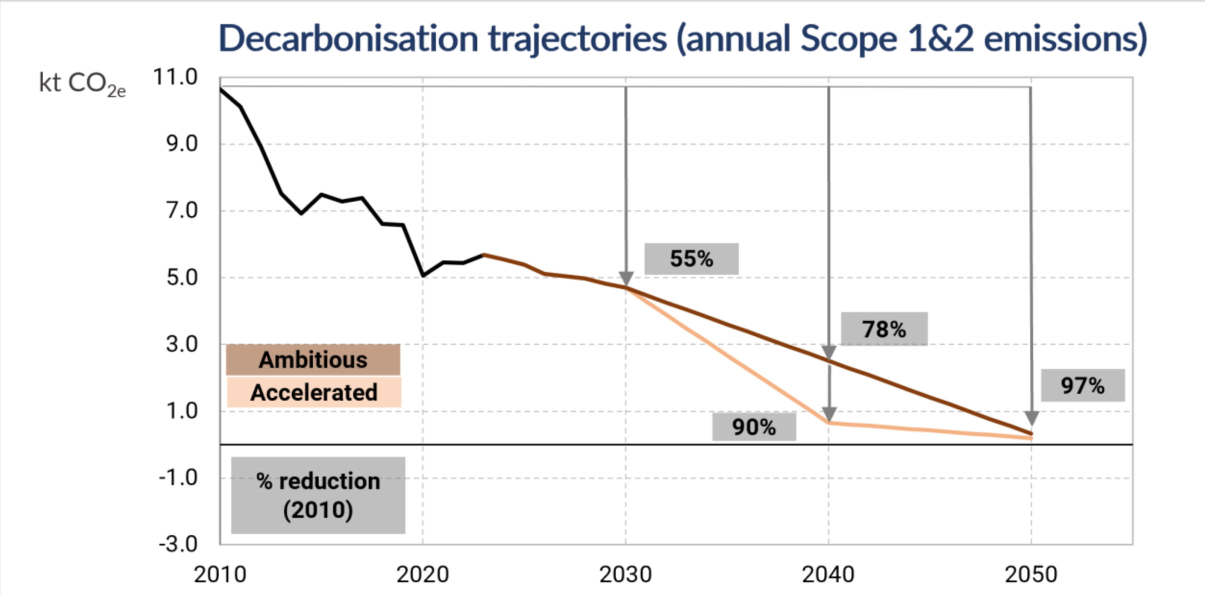


Figure 6 – Ambitious and Accelerated scenarios for decarbonisation trajectories.

4.2.4 Technological and non-technological solution pathways

Taking the example from the methodological approach spread by ACI Europe through the analysis of the Roadmaps that have been already uploaded in the common repository [11], the solution pathways adopted can be ranked under 7 different categories that can be seen in below Figure 7.

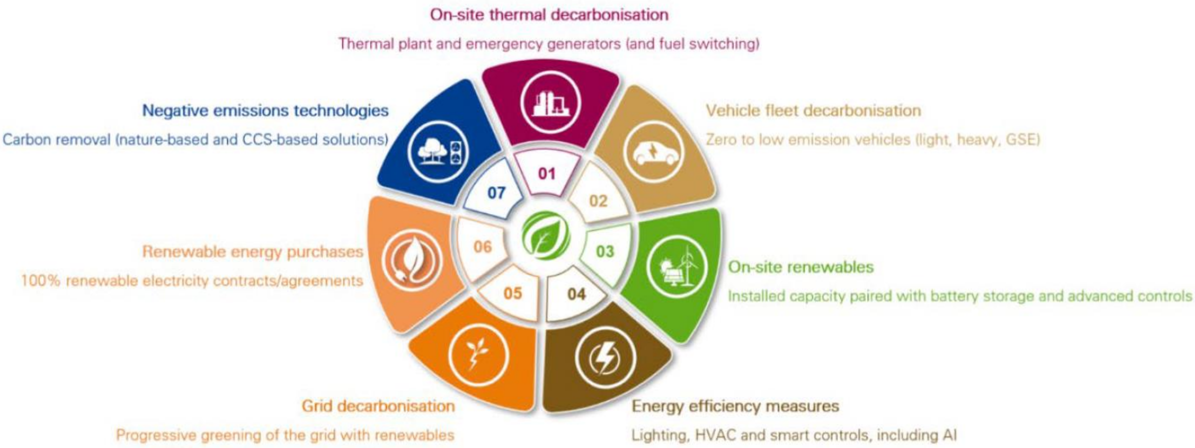


Figure 7 - Classification of interventions according to ACI roadmaps.

In the following paragraphs the main solutions adopted and considered inside the model will be described. The perimeter of the analysis carried on insists on the Scope 1 and 2 emissions/consumptions of the airport.

On-site thermal decarbonisation

Different solutions have been modelled to reduce the impact of fossil fuel on thermal demand:

- Heat pumps: it has been considered the possibility of replacing currently installed boilers with heat pumps in order to move some of thermal load to electrical and exploit better the presence of RES on site. This solution is particularly useful also in buildings that at the moment are far away from the main terminal and thus still fuelled with diesel oil;
- Fuel cell: the airport has begun some years ago reasoning on the installation of a trigeneration system that could be flexible in terms of fuel inlet and with higher electrical efficiencies if compared to the state-of-the-art trigenerations systems based on internal combustion engines. This element has been comprised in the analysis with the study of a SOFC based Fuel Cell with small modules of 250 kWe. This solution allows in medium time to pave the way to decarbonisation of thermal consumptions, considering that can be fed not only with methane but also with increasing blends of H_2-CH_4 until 100% H_2 of fuel inlet.

Vehicle fleet decarbonisation

The airport has already started a pathway for the switch of the vehicles present inside the airport premises form fossil based to electrical vehicles or hybrid. Inside the model it has been considered the full electrification of the current demand related to fossil fuel for ground transportation. The same consideration has also been made on vehicles related to handling purposes, even if this energy demand would not be strictly inside Scope 1 and 2.

On-site renewables

One of the focuses of the airport targets to 2030 is the increase in the self-consumption of renewable energy produced on site. For what concerns renewable energy systems the only technology considered is solar. The considerations made have started from the availabilities in terms of surfaces present at the airport.

In particular, two kinds of availabilities are present: rooftop surfaces for rooftop installations and ground areas for larger installations. The overall installation can arrive to a power of about 6 MWp.

Considering the current legislation in Italy that strongly affects the energy produced but not consumed locally (its remuneration is around 40% of full price usually purchased from the grid) inside the model it has also been considered the possibility to store electrical energy during peak hours inside batteries to maximise self-consumption.

Energy efficiency measures

For the airport energy efficiency has been the first pillar on which has been based the decarbonisation strategy, and even if the major impact solutions have already been carried on during the last decade reduction of primary energy demand is still one of the main focuses of the airport strategy to reach 2030 objectives internally set.

In this framework different solutions have been considered inside the analysis:

- LED lighting: the airport has already provided to the substitution of the most profitable old technology lighting reaching the 60% of LED coverage in terms of energy consumption for lighting needs, but it is still possible to gradually proceed with the goal of getting nearer and nearer to 100% LED lighting;
- HVAC: air conditioning is one of the main consumptions of the Terminal both in terms of electricity and in terms of thermal needs. Some optimisations in terms of management have already been carried on during the last years but there are still some margins in the improvement of the performances of the HVAC systems. In particular there are some units that have been installed in the early ‘90s and that can be revamped installing high efficiency motors and verifying the flow rates currently needed for the ventilation of the areas. This intervention could lead both to higher thermal and electrical efficiencies;
- Thermal boilers: it has been considered the substitution of the main boilers with newer ones and higher efficiencies in the production of hot water. Another possible efficiency is related to the lowering of the temperature of the circuit that will allow both to increase the efficiency during the production of hot water (exploiting better the characteristics of condensing boilers) and to reduce the overall thermal demand of the areas;
- Electrical grid optimisations: with the technology evolutions that have occurred inside the airport premises some optimisation possibilities can emerge in terms of load balance of the different electrical cabinets present. In particular exploiting the requests emerged by the distributor it could be lowered the medium voltage ring that distributes electrical energy through the airport. This will imply the substitution of transformers with the opportunity to increase the transforming efficiency of the machines installed;
- Fuel cell based trigeneration: the solution analysed and previously explained allows not only the reduction of emissions introducing the possibility to use hydrogen, but also implies an higher efficiency thanks to the very high electrical efficiencies and the combined production of heat and power (in winter supplying the waste heat to the hot water loop and in summer thanks to the absorption chiller contributing to the chilled water demand of the terminal).

Grid decarbonisation

Considering the historical trend on decarbonisation deriving from data provided by ISPRA [12] an estimation of future grid carbon intensity can be made, assuming that the emissions are linearly correlated to the amount of electricity generated by the thermal park. These calculations have been used inside the model to account for emissions related to electrical purchase from the grid.

Renewable energy purchases

Different considerations have been made on renewable energy purchases.

For what concerns fuels, different considerations have been made according to the scenarios analyzed:

- Biomethane: it has been considered as a viable solution in accordance with the biomethane potential present in Italy through the purchase of Guarantees of Origin. At the moment, legislation is still in progress at national level, but considering the targets set for 2030 it has been supposed an availability of biomethane on the market and purchasable by the airport comparable to the economic size of the management company. The reasoning behind this assumption is related to the fact that not only airports will aim to acquire biomethane, but also for other companies it will be an easy way to decarbonize the thermal demand (particularly for industry);
- Hydrogen: presently, there is no market nor infrastructure for importing hydrogen from outside the airport boundaries. For this reason, different assumptions have been made for regarding its availability. A more strict focus will be made inside the scenarios analysis but different considerations have been made on the availability of hydrogen both for what concerns self-production through the use of electrolysers during peak hours of electrical production form the PV plants installed and for what concerns external supply from the grid (in the medium term). The birth of the Piedmont Hydrogen Valley (seven projects eligible, with three receiving immediate financing) represents an opportunity to produce hydrogen. Initially, the renewable hydrogen produced will cater to Piedmont production companies' industrial processes, but the future holds broader applications

Negative emissions technologies

Negative emissions technologies have not been considered inside this analysis.

4.3 Modelling framework implementation

This section of the report deepens on the features of the modelling framework used and describes the modelling choices made to translate the real energy system of the airport in a simplified mathematical representation. The main modelling assumptions, concerning model's boundaries and temporal, spatial and technological aggregation, are discussed. In the last subsection, the way in which uncertainties were handles is described.

4.3.1 Modelling framework description

The methodology, amply discussed in section 4.1, relies on an integrated mathematical representation of the airport energy system, which was implemented in the OSeMOSYS framework. OSeMOSYS is a fully open-source energy system optimization model, developed by the KTH institute of technologies together with other institutions [13, 14, 15]. Since its launch in 2010, the modelling framework has witnessed a growing popularity and has been enriched with innovative features (e.g., advanced storage modelling [16], elements of smart grid [14]), as testified by the large number of branches maintained on GitHub [17]. In these years, OSeMOSYS has demonstrated a great versatility, being used for energy planning at the national [18], urban [19] and village scale [20].

The OSeMOSYS framework has been developed in the algebraic programming language GNU MathProg, although other versions have been developed in the Python (Pyomo) and GAMS programming environments. The GNU MathProg relies on the python-based *otoole* [21] utility for the management of input/output routines. The model is compatible with a variety of linear optimisation solvers, from the free *GLPK* tool to commercial solvers such as *Gurobi* and *CPLEX*.

The choice of the OSeMOSYS framework was underpinned by a solid review of available energy system models [22]. OSeMOSYS presents a large set of features which makes it a valid instrument for energy planning, also at the airport-scale. The key aspects which influenced the choice were its ability to represent the complex interactions of a multi-energy system, the possibility to model long-term transition pathways and the flexibility of its open-source code, which can be moulded on the specificities of the case under study with relative ease.

From a methodological perspective, OSeMOSYS is formulated as a mixed-integer linear programming model (MILP). Given a set of alternative technologies that concur to the satisfaction of various energy demands, it finds the optimal configuration of the system, that is the configuration which minimises the total system discounted costs, over the entire modelling horizon, under a set of technical, economic and environmental constraints. Thus, from an economic standpoint, the analysis performed by OSeMOSYS is of the Present Worth (PW) or Present Value or Net Present Value (NPV) type. The TSDC can be defined, in a simplified way, as in the following equation:

$Objective\ function$:

$$Total\ \ Costs = \sum_{y,t} CAPEX_{y,t} + \sum_{y,t} OPEX_{y,t} - \sum_{y,t} Revenues_{y,t} + \sum_{y,t} Salvage\ Value_{y,t}$$

In simpler terms, the OSeMOSYS model acts as a computer-based decision maker. Typical decisions made by the model include:

1. Investment in new technologies.

2. Operational decisions concerning the dispatch of energy, such as scheduling of generation, conversion and storage technologies.

Therefore, the decision-making process of the OSeMOSYS model is performed on two different time scales: investment decisions are made on a yearly basis, over the whole modelled horizon; operational decisions are made for each time step. In order to reduce the computational burden inherent to the modelling of several decades with a high temporal resolution (e.g., hourly), the OSeMOSYS model represents a year as a set of representative days.

In order to determine the optimal development pathway, the model needs information on several economic and technical parameters of the energy system, over the entire modelled horizon. In particular, some fundamental inputs are:

1. The exogenously determined demand for energy services (e.g., lighting, cooling, heating, various electric appliances).
2. The technical description of present and alternative technologies, such as conversion efficiencies, emission factors and operational features.
3. Topological description of the energy system, describing energy infrastructures and energy flows.
4. Capital and operational costs of technologies and their evolution.
5. Energy prices and their evolution.

Moreover, the optimality of the energy system is subjected to the satisfaction of a set of technical and environmental constraints. As a fundamental constraint, the selected configuration of the system must be able to satisfy the energy demand in each time step, taking in account of the operational constraints of the technologies. In the base OSeMOSYS code, such technical constraints concern conversion efficiencies, capacity factors for intermittent renewable generation and availability factors to account for annual maintenance.

In addition, the OSeMOSYS model allows to impose environmental constraints, such as:

1. Emission limits. These can be set both on an annual basis, to simulate decarbonization pathways, and on a model-period basis, allocating an overall carbon budget.
2. Renewable targets.
3. Limits on the use of resources. For instance, to limit the availability of local resources, such as biomethane.

The OSeMOSYS model provides as output the optimal development pathway of the energy system for the whole modelled period, specifying the investment decisions for each year and the capital and operational costs needed to implement these decisions. Moreover, it computes the energy balances for each time step of each year, the annual emission and the cash flows relative to the selected configuration of the system. These outputs can be further elaborated outside of the model to derive additional KPIs, such as payback time, renewable shares, primary energy consumption etc.

The OSeMOSYS model was initially developed to model large energy systems, at the national and international level. However, its open-source nature and the flexibility of its code enabled to quickly adapt its formulation to the scale and the specificities of the airport energy system. Among the modifications which were made to the source-code of the model, it is worth highlighting:

1. Improved representation of constraints limiting the operation of technologies, with the introduction of ramping constraints, minimum stable load, limits on the amount of curtailed renewable energy and scheduled maintenance periods.
2. Improved representation of storage technologies, with the differentiation of daily, seasonal and long-term storage types.
3. Introduction of a framework for the optimisation of CHP technologies under the incentive scheme for high-efficiency cogeneration.

4.3.2 Airport energy system model implementation

This section describes the assumptions made to translate the energy system of the airport into the OSeMOSYS framework. The scope of the work is introduced, delineating the airport activities included in the model, the technological options considered and their techno-economic modelling and the temporal coverage and resolution of the analysis.

4.3.2.1 Model boundaries

As described in section 4, the commitment of Torino Airport is to abate the CO_2 emissions in its Scope 1 and Scope 2 activities, till the achievement of the net-zero target by 2050. Therefore, the boundaries of the analysis were primary selected to include all those activities under direct control of the airport, according to the ACA definition. A list of the major activities included is depicted in Figure 8, according to the Scope they belong to. Only energy-related activities were considered. Most of the activities included fall under the Scope 1 and Scope 2 category.

Activities in Scope 1 include emissions from the on-site combustion of diesel oil and natural gas for space heating and generation of sanitary water, as well as the consumption of diesel for company cars. Gasoline consumption, for cars, and LPG, for cooking, consumption was considered negligible and excluded from the analysis. The Scope 1 category also includes potential on-site power generation plants, such as the foreseen CCHP unit. Activities in Scope 2 include the purchase of electricity from the grid for the satisfaction of a variety of services, from space cooling and lighting to the handling of baggage (BHS) and the provision of electricity to landed aircrafts.

A selected subset of Scope 3 activities was included in the model. These include the consumption of electricity by tenants operating on the airport site and the handling of GSE. This because, although these activities do not directly fall under the control of the airport, they could benefit from the generation of on-site renewable electricity in the airport network. As a legal entity, Torino Airport distributes electricity to the external organisation operating in its premises. Tenants represent a relevant 10% of total electricity consumption, whereas the electrification of GSE could open to a similar interaction with airside operators. This could lead to synergies between different stakeholders, with the airport making available green electricity directly to tenants and the latter providing a consumption margin for the integration of further renewable capacity.

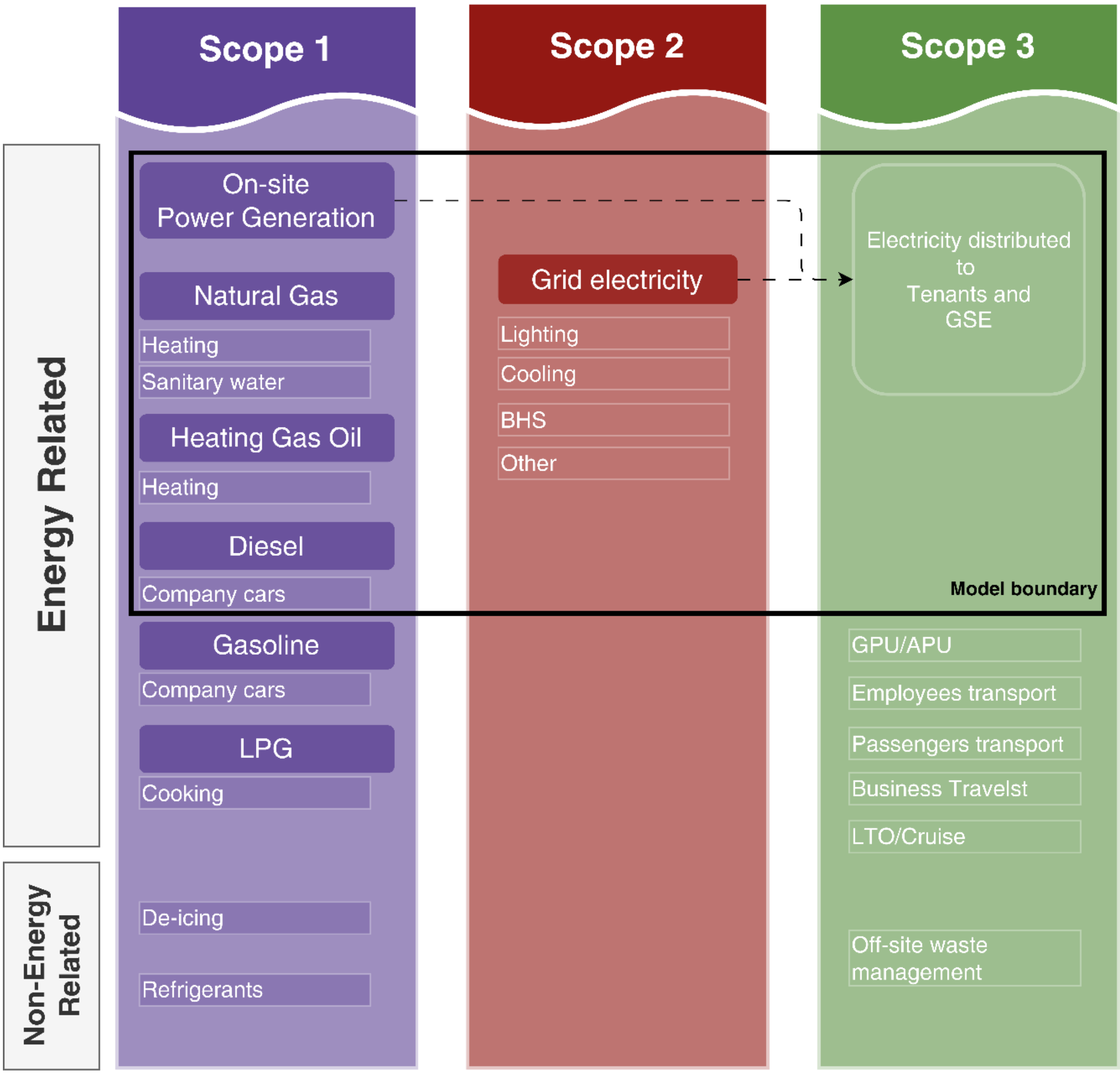


Figure 8 - Classification of airport activities by emission Scope, according to ACA definition. Black rectangles show the activities included in the analysis. These mostly belong to Scope 1 and 2. However, selected activities in Scope 3 were included in the model when potential interactions with activities within airport control could emerge.

4.3.2.2 Energy system representation

Figure 9 shows the representation of Torino Airport energy system in the OSeMOSYS framework. The scheme includes all the technological options and energy carriers presented in section 4.2. Icons in boxes represent technological solutions already part of the airport's assets in 2019, whereas icons without boxes stand for investment options which the model could decide to implement in future years.

The diagram describes all the energy flows of the system, from the import of energy carriers (on the left) to their transformation into the final energy vectors satisfying a demand for a specific service (on the right). The articulated energy system of Torino Airport was simplified in order to enable its representation in the optimisation model. In particular, it was necessary to aggregate portion of the energy system. As shown by the figure, most of the electricity demands were aggregated into *Various Electricity* consumption. Only those demands which are concerned by the implementation of energy efficiency or other technological solutions were separated, such as demand for lighting, cooling, GSE etc.

The heating system was subdivided in three sectors: *Main*, *Secondary* and *Auxiliary*, according to the heat source and infrastructure in place. The *Main* sector include all those equipment and users served by the airport's heating network. The heat is supplied by three natural gas boilers, producing hot water at 90°C, located in the airport's technical area. The *Main* heating sector is prone to the potential integration of the CCHP system, so that part of the heating (and cooling) demand could be satisfied by the SOFC's waste heat. The infrastructure for the distribution of chill water would be the same of that used for hot water. The *Secondary* heating sector represents buildings served by independent heating systems, still powered by natural gas boilers (such as the private flights terminal). The *Ancillary* heating sector represents building served by independent heating systems fuelled by diesel oil boilers (such as hangars).

The transport activities of the airport were subdivided in *company cars*, *heavy maintenance vehicles* and *GSE*. All the fleet is prominently made by diesel vehicles at present, although a growing share of company cars is being electrified. The subdivision was made relatively to the possibility to electrify vehicles and to the scope of the activity. *Company cars*, whose activity falls in Scope 1, and *GSE*, in Scope 3, will be prone to electrification in the coming years. Conversely, the implementation of an electric alternatives for heavy maintenance vehicles, such as snow plows, is more difficult to realise, given the current state of technology.

At the core of the energy system lies a micro-grid concept for the combined generation of electricity, heating and cooling. On-site renewable electricity generation can be achieved though the installation of photovoltaic panels within the airport premises, both rooftop and ground mounted PV. Excess electricity generation can be stored by either electrochemical storage or used to produce hydrogen through an electrolyser. 0.25C Li-ion batteries were selected for electrochemical storage. For the electrolyser, a PEM type was selected, in order to provide flexible start-up/shut-down times, enabling the production of hydrogen from fluctuating solar generation. Hydrogen is compressed and stored at 300 bars in a steel vessel.

The hydrogen produced on-site can be used by another important constituent of the micro-grid: a Solid Oxide Fuel Cell (SOFC). The SOFC can run on different blends of natural gas (or biomethane) and hydrogen, up to a 100% share of hydrogen. The SOFC has a high electric efficiency (62%), but also produces high temperature waste heat which can be exploited for space heating or, by mean of an absorption chiller, cooling. The absorption chiller was assumed to be of the single-stage, water-LiBr type.

Excess renewable electricity production which cannot be stored on-site can be sold back to the utility grid. However, a constraint was imposed on self-consumption of generated electricity, in agreement with ENAC regulation on PV generation on airport sites [23]. Electricity can also be sold to tenants located within airport's premises or used to charge future electric GSE.

Another pack of measures concerns the electrification of heating and transport activities. Currently, space heating demand is satisfied by natural gas and diesel boilers. For these cases, heat pumps were included in the model as potential technological options to electrify the heating sector. Air-to-Water (A2W) heat pumps were selected for this assessment, since this type is already compatible with Torino Airport's heating equipment and does not require major infrastructural expenses [24]. The electrification of the airport's fleet of company cars, already ongoing, is also included in the model.

The only energy efficiency measure considered is the conversion of conventional light bulbs to LED. This because Torino Airport has already undergone an intensive period of efficiency improvement, as testified by the drop of its energy consumption since 2006, so that only minor interventions remain on that side. Measures targeting building envelop of smart energy management systems were not included in this stage of the analysis, due to the complexity of modelling a complex building environment such as that of an airport. These should be investigated in a future work.

Finally, the supply of alternative energy carriers was considered. These include biomethane, biodiesel and hydrogen. Biomethane was assumed to virtually enter the system through the purchase of Guarantees of Origin, as envisaged by the Italian Ministerial Decree 15/09/2022 and in line with ACA market-based approach. Using this approach the airport would purchase natural gas from the existing grid and an energy equivalent biomethane GO from the dedicated market [25]. In this way, it could claim the use of renewable biomethane, injected in the gas grid at whatever location, in substitution of its natural gas consumption. The establishment of a dedicated supply line from local producers, which could provide an alternative access to this resource, was not considered because of difficulties in quantifying the infrastructural costs needed to secure a relevant biomethane supply.

The availability of an external hydrogen supply was envisaged to simulate a scenario in which the Torino Airport is involved in a local Hydrogen Valley project, whose development is foreseen by the

Italian national energy plan [26, 27]. Several Hydrogen Valley projects are foreseen in the Piedmont region for the future years [28], which justify the consideration of an external hydrogen supply.

Green diesel is only foreseen as a substitute of fossil diesel for the operation of heavy vehicles (such as snow plows) whose electrification appear, at present, infeasible. An HVO made from used cooking oil was considered.

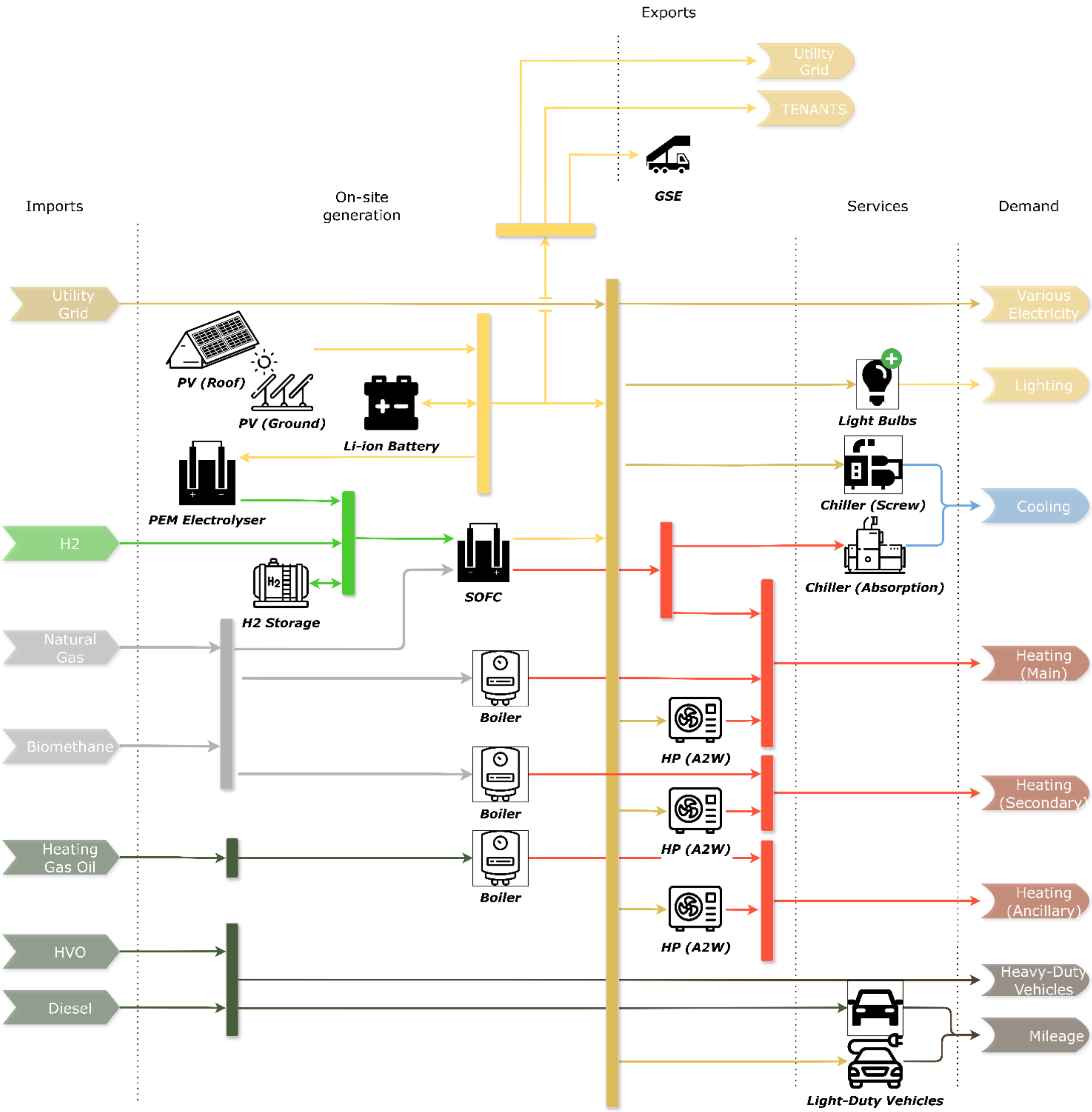


Figure 9 - Simplified representation of Torino Airport's energy system within the OSeMOSYS framework. Boxed icons represent technological assets already existing in 2019.

4.3.2.3 Temporal coverage and resolution

Two temporal dimensions exist in the OSeMOSYS framework: operational and investment. The investment dimension defines the temporal parameters over which investment decisions are made. Important criteria in this dimension are the model horizon, that is the period over which investment decisions are optimised (e.g., 2030, 2040, 2050), and the length of investment cycles (e.g., one, three, five years). This latter parameter defines the resolution with which the model makes investment decisions. The operational dimension concerns the time step over which decisions are made on the dispatch of energy and the operation of storage technologies. Important criteria in this dimension are the choice of the number and type of typical days used to represent a full operational year of the airport and the choice of the time step, that is, the time unit over which dispatch decisions are made.

A summary of the temporal parameters used in the analysis is provided in Table 3.

Table 3 - Summary of the parameter defining the temporal dimension of the model.

Temporal dimension	Parameter	Definition	Value
Investment	Validation years	*Years of known airport operations, used to validate the model*	2019-2023
	Horizon	*Period over which investment decisions are made*	2024-2050
	Investment cycles	*Resolution of the investment decisions*	1 year
Operational	Typical days	*Number of days used to represent a full operational year*	9[1]
	Time step	*Time unit over which dispatch decisions are made*	1 hour[2]

[1]One typical day for each month from March to October, one typical day for winter months.

[2]Closing hours of the airport (00:00-5:00) were aggregated in a single time step.

4.4 Robust smart energy hub concept(s)

This final section describes the outcome of the study, presenting the most relevant results extracted from the numerical campaigns conducted for the project. The section opens with some preliminary considerations made on selected technological options, PV, SOFC and hydrogen production, providing the reader with a background on the economic and environmental performance of these solutions. Then, the optimal configurations of the system under stated targets (*Ambitious* decarbonisation scenario) are presented for the three technological pathways explored (H2, H2_IMP, ELCTR). Subsequently, the results relative to the *Accelerated* target scenarios are showed, highlighting the variation of the energy system configurations and costs necessary to achieve a steeper decarbonisation trajectory. Finally, the economic risks associated with each development pathway are assessed by testing their performance in alternative future scenarios. In conclusion, the main outcomes of the study are discussed, evaluating the risks and benefits inherent to specific technological pathways, and a concept for a robust energy hub for Torino Airport is developed.

4.4.1 Presentation of modelling results

4.4.1.1 Preliminary evaluation of technological options

Before delving deep into the results of the numerical campaigns conducted with the energy planning model, it is useful to introduce a preliminary technical, economic and environmental assessment of the core technologies of the energy system. To this aim, this section presents a discounted pay-back time analysis and environmental assessment of the SOFC and PV system. Moreover, some reflections are presented on the feasibility of hydrogen production within the airport premises.

SOFC. The pay-back time and environmental assessment of the CCHP system based on the SOFC are presented in Figure 10. A 0.25 MW fuel cell was considered, and it was assumed that it would be installed in 2027. The fuel cell is assumed to be fuelled by a 100% natural gas blend. The payback time is calculated for three energy price scenarios taking in account of the monetary savings with respect to separate generation of heating and cooling and purchase of electricity from the grid. The calculation of emission savings is also calculated comparing the CCHP system to separate generation. A reduction of electricity grid carbon intensity is assumed as described in Annex **Error! Reference source not found.**.

Despite the high initial investment, the SOFC-based system appears to repay itself in 4 to 7 years, depending on the energy price scenario. In particular, the higher the cost of energy, the quicker the investment is repaid, thanks to the high electrical efficiency of the fuel cell, which allows to attain significant monetary savings also under high natural gas prices. This is valid under the assumption, made in section that electricity and natural gas markets remain coupled (see Annex A).

From an environmental perspective, it is noted that, despite the high efficiency of the fuel cell, a solution based on 100% natural gas blend does not produce, already in 2027 any environmental advantage. Operating a 0.25 MW SOFC would raise emissions by nearly 0.2 $kt_{CO_{2e}}$ in 2027 with respect to separate production, with this figure ramping to nearly 0.5 $kt_{CO_{2e}}$after 2040, as the electricity grid decarbonises.

Therefore, the CCHP system based on SOFC fuelled by natural gas presents itself as a solution having high economic performance but poor environmental benefits, also in the short-term. The integration of alternative fuels, such as biomethane and hydrogen, should thus begin very early in order to avoid additional emissions. However, this would entail additional costs related to the price of these alternative energy carriers, which could weaken the economic feasibility of the CCHP system.

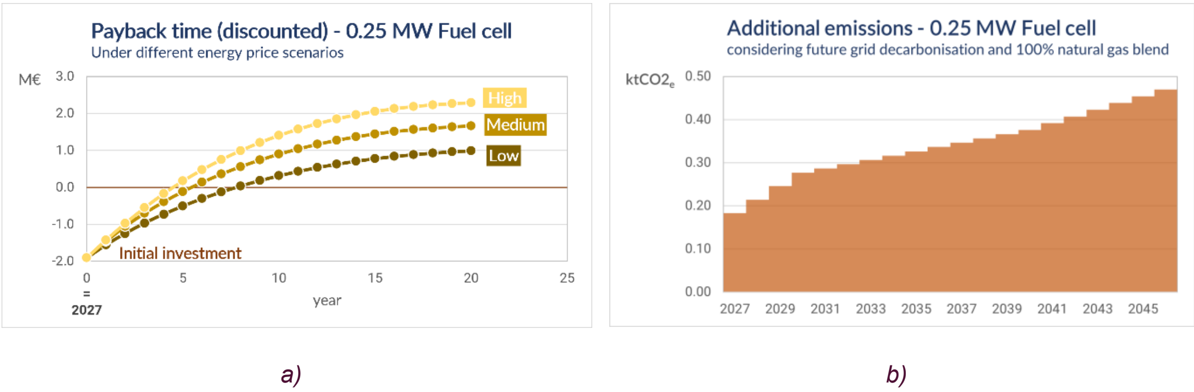


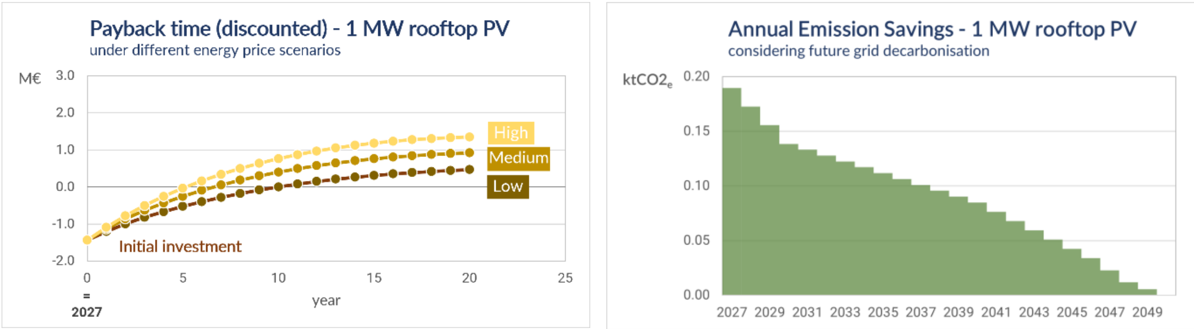
Figure 10 – Payback time (a) and additional emissions with respect to separate generation (b) of the CCHP system with SOFC.

PV. A similar analysis has been conducted for a $1\ MW_p$ rooftop PV system (Figure 11).For this size of the system, it is possible to assume that all the electricity produced will be consumed by the airport's own demand. This assumption, which does not hold for higher power installations, can handled by the energy system optimisation model. The savings are calculated with respect to the counterfactual case in which the electricity is withdrawn from the grid.

It can be noted that, from an economic perspective, the PV system appears less attractive than the CCHP, with payback times ranging from 5 to 10 years, depending on the energy price scenario. Nevertheless, the solution can still be considered economically viable in the long-term, especially for high energy price scenarios, due to the long lifetime of the selected PV panels (25 years).

Contrarily to the CCHP system, the PV demonstrates high potential for emission savings in the short and medium term, when compared to the electricity from the grid. However, it is important to notice that, as the electricity grid gets decarbonised, the ability of the PV to deliver emission savings decrease (from nearly $0.20\ ktCO_{2e}$ in 2027 to practically $0\ ktCO_{2e}$ in 2050). This means that, in the future years, it will be necessary to install more PV power to obtain the same emission savings that solar power can deliver in these days, so that purchasing grid electricity might become more convenient.

It must be underlined how for the PV system, the economic and environmental objectives can be pursued with the same technological option, contrarily to the CCHP system fuelled by natural gas.



a) *b)*

Figure 11 - Payback time (a) and emission savings with respect to grid electricity purchase (b) of a $1MP_p$ rooftop PV system.

On-site hydrogen production. In the developed model, hydrogen can be made available to the airport either by on-site electrolysis absorbing excess PV generation or through an external supply. While the feasibility of the latter options strongly depends on the development of the local energy system, as well as on the national and international establishment of a hydrogen economy, the production of hydrogen on-site could be independently implemented by the airport. Nevertheless, the amount of hydrogen which can be produced within the airport's premises is limited by the availability of space for renewable installations [29], whereas the economic viability could be challenged by the relatively low power-to-power conversion efficiency of this pathway.

Figure 12 shows a summary of back-of-the-envelope calculations made to assess the feasibility of on-site hydrogen production. The left figure shows the load curve of excess renewable generation for a $10\ MW_p$ PV system, which is the maximum installable size due to space limitations. The excess renewable generation does not account for the increase in electricity demand induced by electrification measures, nor considers batteries or export of electricity. It thus represents a maximum technical potential for hydrogen production at the airport. The left figure also shows the hours of operation and the relative hydrogen production for different electrolyser sizes (in MW_e). It can be observed that, also assuming a 0.5 MW_e electrolyser, this would work for slightly more than 2500 hours per year at full load. As the size grows, the full-load hours decrease swiftly, being less than 1000 for a $3.0\ MW_e$ electrolyser.

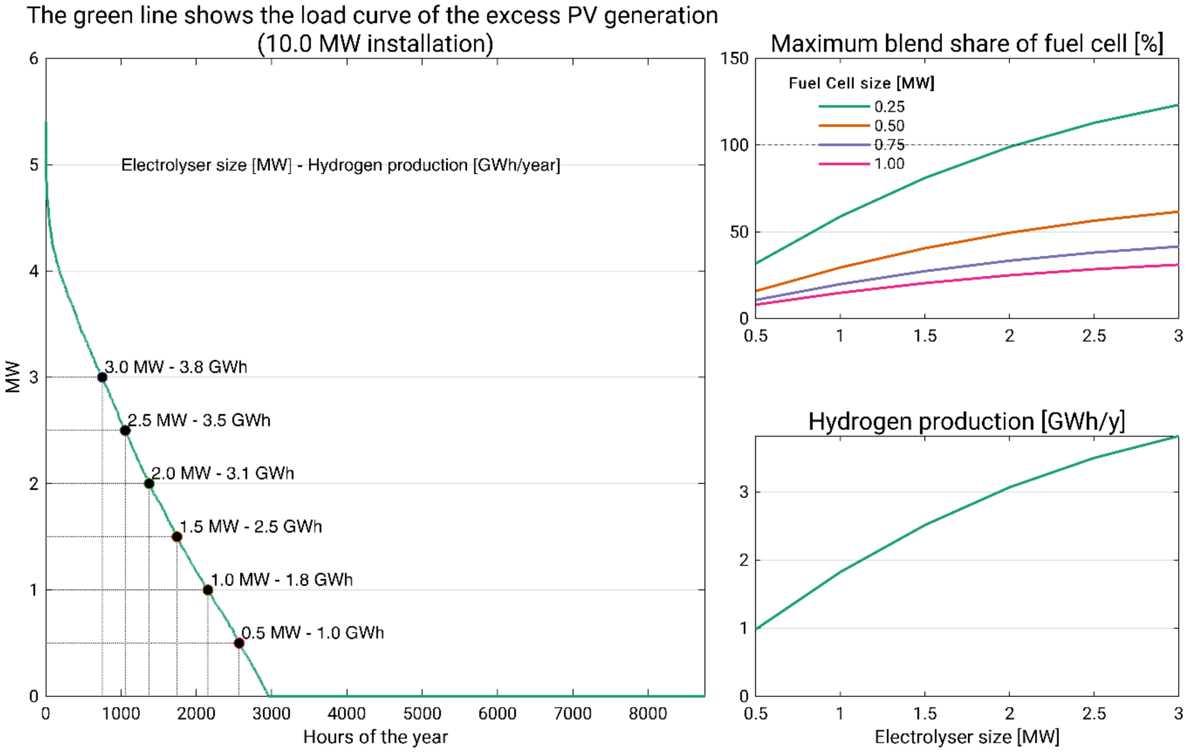


Figure 12 - Estimation of hydrogen production potential at the airport site during one year of operation.

Left figure shows the load curve of the excess renewable generation of a 10 MWp PV system (maximum size considered, due to space availability). The figure also shows hours of operation of electrolysers of various sizes and the respective hydrogen production. Bottom right figure shows maximum hydrogen production potential for different electrolysers sizes, whereas top right figure reports the (energy) share of the fuel cell's blend which can be covered by the hydrogen produced on -site.

The right figures illustrate on-site hydrogen production potential. The bottom one reports the absolute value of hydrogen produced in one year for electrolysers of various sizes. Moving from a 0.5 to a $3.0\ MW_e$ electrolyser, hydrogen production moves from about $1\ GWh$ to nearly $3.5\ GWh$. The top-right figure shows the portion of fuel cell blend (as percentage of energy content) which can be covered by such hydrogen production. Despite the simplified nature of these preliminary calculations, it appears clear that to sustain a small-size fuel cell ($0.25\ MW_e$) entirely with on-site production of hydrogen would require an investment in an electrolyser of at least $2.5\ MW_e$, which would work for approximately 1000 hours per year. As the size of the fuel cell increases, on-site hydrogen could cover less than 60% of the fuel cell blend, in face of significant investment in underutilised electrolyser capacity.

From these preliminary calculations, it appears that hydrogen economy entirely based on production at the airport site would be unfeasible, especially for large fuel cell sizes. It can be expected that external hydrogen supply, together with the availability of biomethane as an intermediate energy carrier, would be key enablers for a successful hydrogen economy.

4.4.1.2 Technological pathways

This section presents three different technological pathways through which Torino Airport could achieve its stated decarbonisation objectives. The three technological pathways, denominated *ELECTR*, *H2* and *H2_IMP*, aim to describe the optimal evolution of the airport energy system under different strategical choices (for details, see section 4.2). All the pathways were simulated under the *Baseline* scenario assumptions (see Annex A), with the *Ambitious* decarbonisation trajectory.

Emissions reduction. Before delving into the description of the configuration of the energy system, it is useful to look at the performance of the different technological pathway under the emissions perspective. This because emissions reduction is supposed to drive investment in sustainable technologies in the model, being thus the main driver of the development of the energy system.

The emissions reduction trajectories are shown in Figure 13. The reader is invited to notice that, in agreement with the implementation of the optimisation model, all the development pathways are constrained to deliver an emissions reduction equal or higher than the imposed trajectory (black dotted line).

The way decarbonisation targets are achieved differs significantly in the three technological pathways. For the *ELCTR* scenario, the decarbonisation trajectory is steadily downward and always well below the imposed trajectory. Although after 2040 this trend is determined by the imposed phase out of fossil fuels, this also indicates the synergy, in this pathway, between the economic and the environmental objectives: investment decisions are not taken solely to reduce the carbon footprint of the airport, but to pursue an economic benefit as well.

For hydrogen-based pathways the trend is quite similar to the *ELCTR* one until 2030. However, decarbonisation trajectories stall in the first half of the 2031-2040 period, and only begin to fall again when they meet, in the second half of the period, the imposed decarbonisation trajectory. As it will be shown later, this trend is due to the installation of the fuel cell, which is able to deliver significant economic savings when fuelled by natural gas, but which at the same time implies additional emissions (Figure 22). This determines an opposite situation with respect to the *ELCTR* scenario, since to ensure a low carbon intensity blend for the fuel cell it is necessary to invest in more costly fuels (hydrogen and biomethane) from the second half of the 2031-2040 period, which decreases its economic benefits.

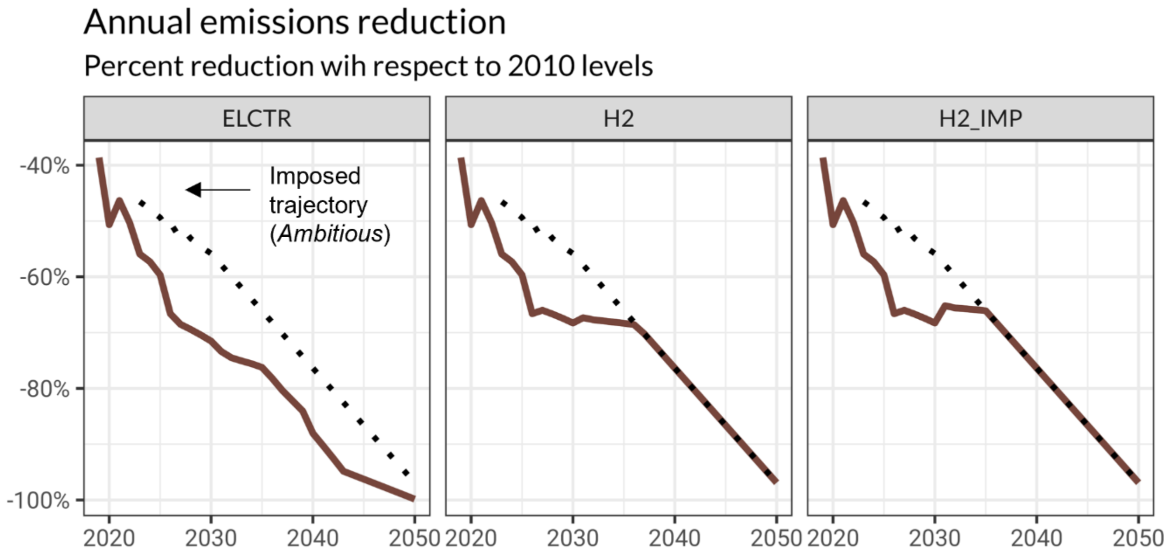


Figure 13 - Emissions reduction trajectories (with respect to 2010) of the three technological pathways under the Ambitious *decarbonisation scenario.*

Figure 14 provides an overview of how different clusters of measures contribute to the emissions reduction, calculated with respect to 2019 situation. For the *ELCTR* pathway, the PV plays an important role since the beginning of the modelled period. Switching to alternative fuels, like biomethane for heating, plays a relevant role in only in the second half of the 2031-2040 period; then, electrification gains momentum, in agreement with the imposed phase-out of fossil and non-fossil fuels. Towards 2050, about two third of emissions reduction are delivered by PV and electrification. However, the airport relies significantly on the decarbonisation of the electricity grid to achieve its targets.

For the *H2* and *H2_IMP* pathways the emissions reduction patterns are similar and show a richer diversification of measures with respect to the *ELCTR* one. The PV system continues to play a significant role in the decarbonisation. Conversely, the role of electrification measures is taken by the switch to biomethane for heating and, partly, by the exploitation of waste heat from the CCHP system. The latter brings a growing contribution to the decarbonisation starting from the second half of the 2031-2040 period, especially for the *H2_IMP* scenario in which, we will see, the penetration of the fuel cell is larger.

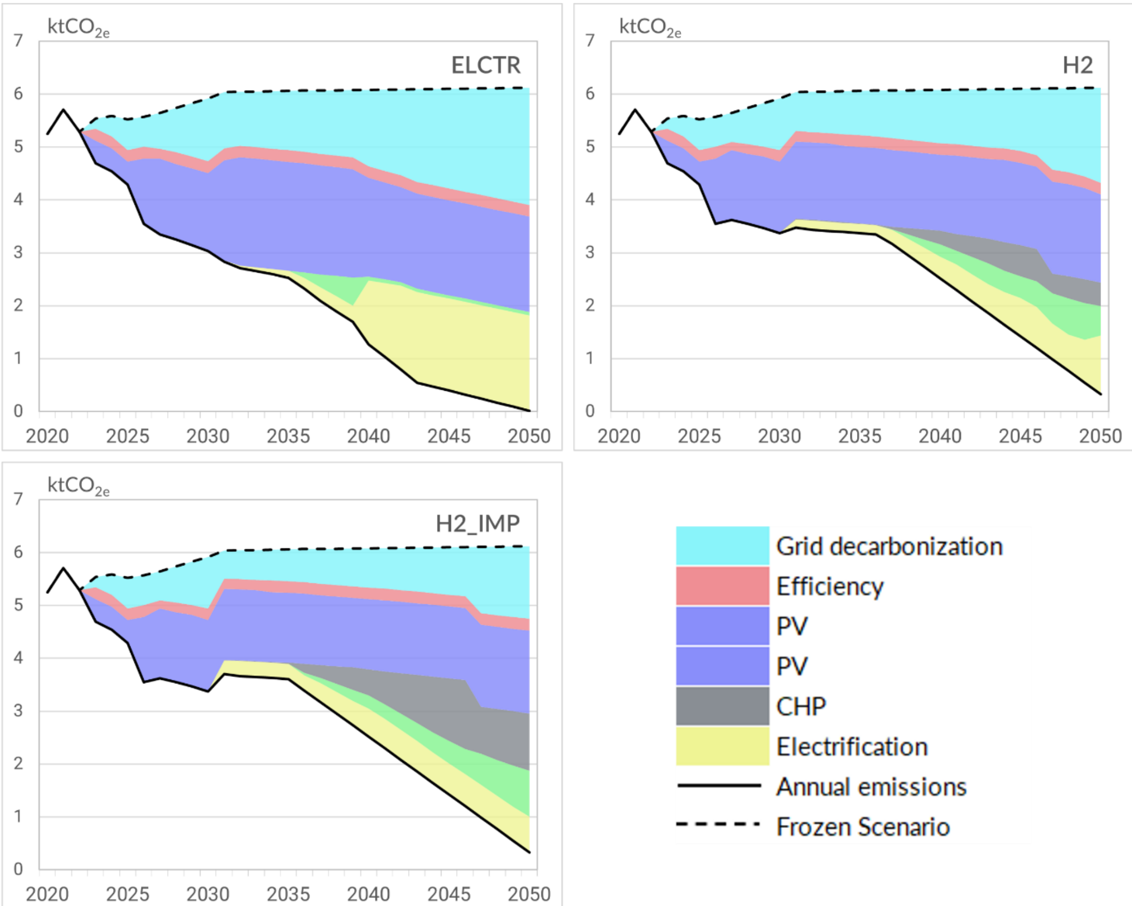


Figure 14 - Contribution of cluster of measures to the reduction of emissions. Electrification: electrification of transport and heating; Fuel Switching: substitution of fossil fuels with HVO and biomethane (except the share used for CHP); PV: renewable electricity generation, comprising battery discharge; Efficiency: efficiency measures (lighting); CHP: fuel cell cogeneration system, including use of green fuels (biomethane and hydrogen); Grid decarbonisation: reduction of carbon intensity of the electricity grid.

Configuration of the energy system. It is interesting to observe how the configuration of the energy system and the provision of energy to the airport change under different technological pathways. **Error! Reference source not found.** to Figure 17 show the energy balance for several energy carriers of interest: electricity, main and ancillary heating, biomethane and hydrogen.

With reference to Figure 15, all the technological pathways see a significant penetration of PV capacity. The installations begin in the 2024-2030 period, reaching around $6.5\ MW_p$ already in 2030. No storage technologies are installed in this period, and excess electricity generation is sold to the grid, up to 30%, or sold to tenants. Still in the 2024-2030 period, the model installs a $0.25\ MW_e$ SOFC for both the *H2* and *H2_IMP* pathways.

In the 2031-2040 period major differences emerge between the technological pathways. In the *ELECTR* pathway investments in PV capacity continue steeply, reaching the maximum available capacity ($10\ MW_p$) already in 2035. The increased renewable generation is partially absorbed by the higher electricity demand dictated by increased airport activities and electrification, especially at the end of the period (Figure 15). However, this would not be sufficient to absorb the increased renewable output, so up to 5.0 MWh of Li-ion battery capacity (1.25 MW in power capacity) is installed shortly after 2030. In 2040, nearly half of the airport's electricity demand is covered by the PV and battery system.

In the same 2031-2040 period, the *H2* and *H2_IMP* pathways see further investment in the SOFC system, due to the drop in fuel cell capital costs. In the *H2* pathway the total SOFC size reaches $0.50\ MW_e$, whereas $0.75\ MW_e$ are installed in the *H2_IMP* one. This difference will be better explained in the following paragraphs, when describing the 2041-2050 period. In both the hydrogen pathways, PV capacity grows slower, stopping at around $7.2\ MW_p$ in 2040. This because the baseload provided by the fuel cell makes it harder to absorb additional renewable generation. In parallel, $2.0\ MWh$ battery capacity is early installed at the beginning of the period. Conversely, moderate hydrogen production only starts in the second half of the 2031-2040 period (Figure 17). In the *H2* pathway up to $0.15\ MW_e$ electrolyser is installed before 2040, for an annual hydrogen production of $0.17\ GWh$, whereas up to $0.35\ MW_e$ are installed in the *H2_IMP* pathway, for an annual production of hydrogen of up to $0.40\ GWh$. Larger hydrogen production capacity is required in the *H2_IMP* because of the larger fuel cell size, which determines more excess PV production as well as a higher consumption of fuel for its operation, which has to be made more sustainable with larger shares of hydrogen.

2031-2040 is also the period in which the diversification of energy sources for heating and natural gas begins (Figure 16 and Figure 17). This is particularly evident for the *Ancillary Heating* segment, presently fuelled by diesel boilers. These technologies, which are both more expensive to operate and more carbon intensive than natural gas boilers, are completely substituted by heat pumps before 2040 in all the technological pathways. The situation is more convoluted for the *Main Heating* segment. In the *ELCTR* pathway, for which a phase-out trajectory was imposed for natural gas, negligible investments in heat pumps capacity are observed before the end of the period, and the heating sector is mainly decarbonised through the purchase of biomethane.

For the hydrogen-based scenarios, the electrification of the *Main Heating* segment already starts at the beginning of the 2031-2040 period. This is due to two main causes: first, the installation of fuel cells unlocks the possibility to generate low-cost electricity throughout the day, decreasing the operating costs of heat pumps and making them more competitive with gas boilers; second, as it will be discussed more in depth in the paragraph dedicated to CO_{2e} emissions, the installation of fuel cells initially fuelled by natural gas lead to the necessity to lower emissions in other sectors of the energy system (e.g., through electrification of heating). Moreover, in the hydrogen scenarios the waste heat recovery contributes to the satisfaction of the main heating demand, although only modestly: about 10% and 16% of total heating demand in 2040 for the *H2* and *H2_IMP* pathways, respectively.

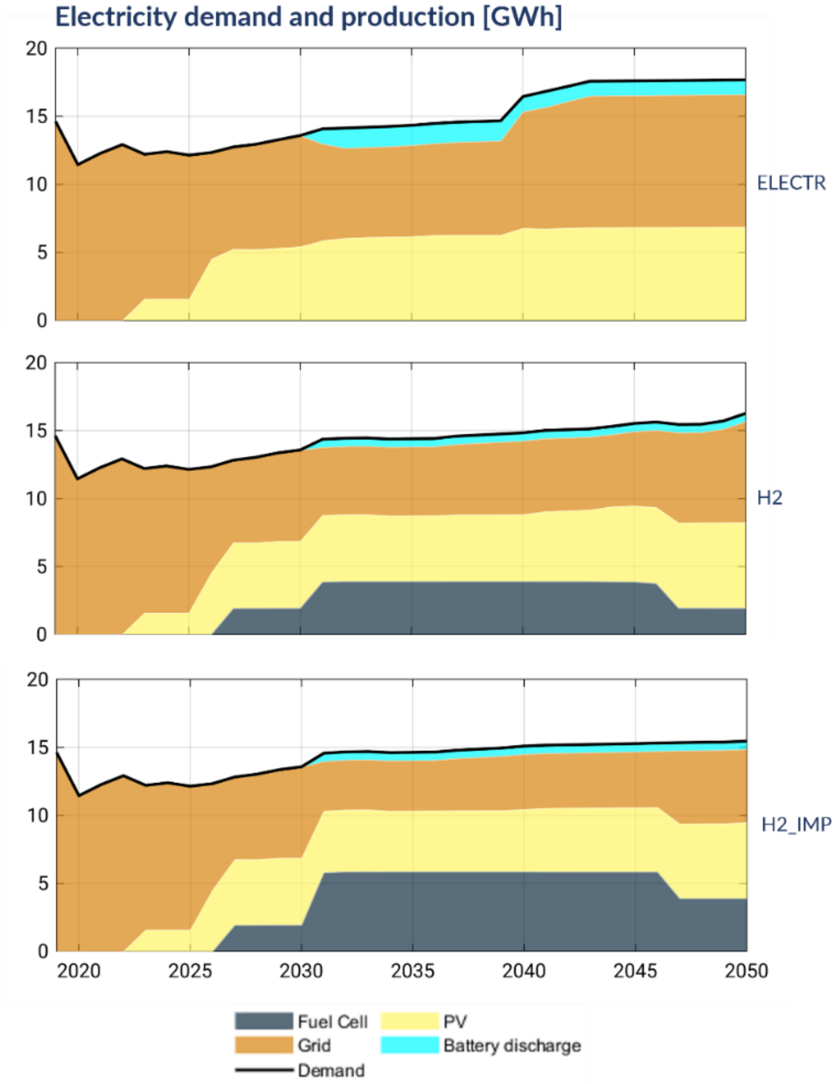


Figure 15 - Electricity demand and production at Torino Airport in the three technological pathways under the Ambitious *decarbonisation targets.*

A significant portion of the *Main Heating* demand is still satisfied by natural gas boilers in 2040 for the hydrogen-based scenarios. However, the share of biomethane increases in the natural gas mix increases towards the second half of the period, reducing the carbon intensity of the heating sector as well as contributing to the greening of the fuel cell blend. It is however noted that, despite the increasing share of biomethane, in 2040 the demand for fossil natural gas is still higher than present, due to the increased demand determined by the installation of the fuel cell. It is worth reminding that, despite the increased natural gas demand, the hydrogen-based scenarios still respect the emissions reduction trajectories set by the *Ambitious* scenario.

The 2041-2050 period sees the early electrification of the heating sector for the *ELCTR* pathway, in compliance with the imposed phase-out of natural gas. As a consequence, the electricity demand of the airport rises close to 18 GWh, a nearly 23% increase with respect to 2019. As the PV capacity has already been saturated in the 2031-2040 period, the additional electricity demand is entirely covered by the grid. However, a modest increase in the self-consumption of renewable electricity, together with a reduction in the operation of the battery, is determined by the increased electricity demand.

As concerns the hydrogen-related pathways, a similar pattern is observed. Both pathways have been characterised by significant investment in fuel cell capacity in the previous periods, driven by the economic advantages deriving from the high electric efficiency and cogeneration. Nevertheless, these economic savings are effective only when the fuel cell is fed by natural gas. Switching to cleaner but more expensive fuels, such as biomethane and hydrogen, reduce the economic competitivity of the fuel cell, to the point that part of the capacity is decommissioned when it reaches its end of life (n.b., 20 years) and no further investment are made.

This holds particularly true for the *H2* pathway ($0.25\ MW_e$ fuel cell in 2050), in which the only way to provide a green blend to the fuel cell is through the purchase of expensive biomethane or through the on-site production of hydrogen. This latter solution, in particular, is not considered particularly viable, due to the high costs entailed by the additional PV and electrolyser capacity and overall low conversion efficiency of the power-to-power system. In 2050, total PV capacity reaches the maximum of $10\ MW_p$, while the electrolyser capacity rises to $0.80\ MW_e$, for an annual hydrogen production of less than $1\ GWh$.

For the *H2_IMP* pathway, a similar pattern is observed. However, the availability of an external hydrogen supply at an affordable price (n.b., 2.0 €/kg, including infrastructure costs), enables the upkeep of a $0.50\ MW_e$ fuel cell. Of course, this is strongly dependent on the availability of such low price hydrogen, which would be strongly dependent on the modality and on the volumes of the supply. Due to the availability of a cheaper hydrogen supply, the on-site production of hydrogen does not see significant changes in this period and, consequently, also investment in PV capacity stops at $9.0\ MW_p$.

As concerns the heating sector, electrification proceeds slower than in the *ELCTR* scenario (in which the phase-out of natural gas and biomethane was imposed). Still in 2050, a mix of waste heat, heat pumps and gas boilers fuelled by biomethane provides the best trade-off between emissions reduction and economic performance.

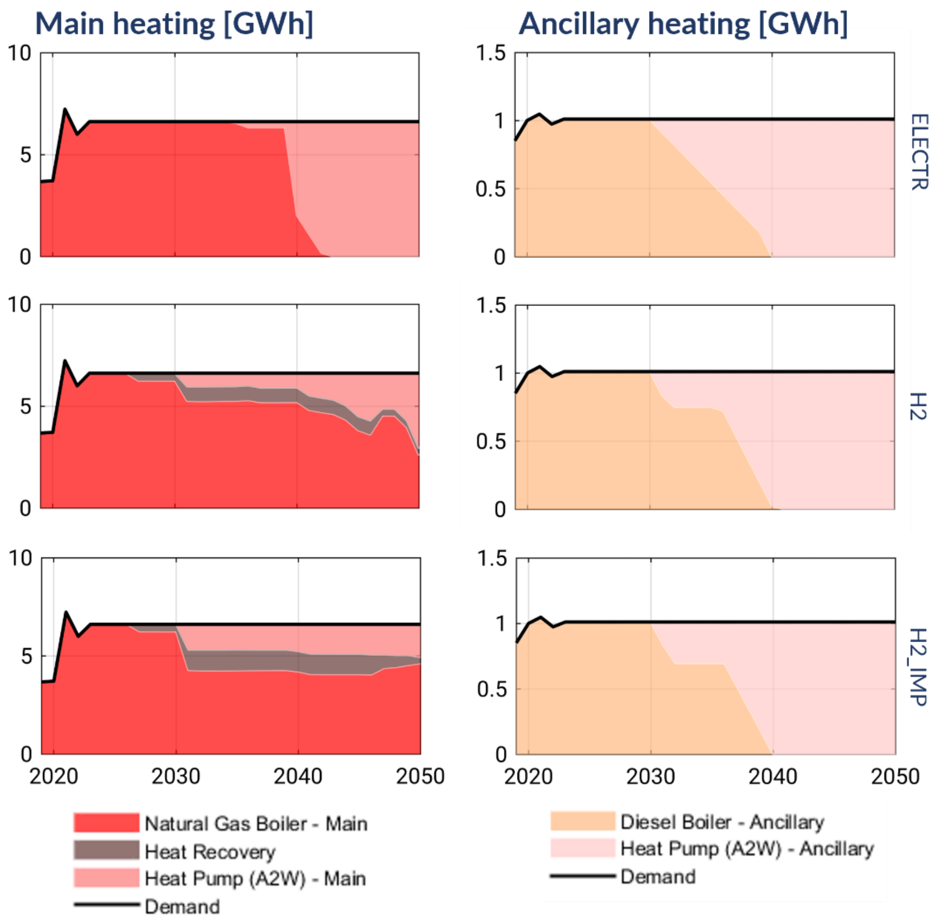


Figure 16 – Main and Ancillary heating demand and production at Torino Airport in the three technological pathways under the Ambitious *decarbonisation targets.*

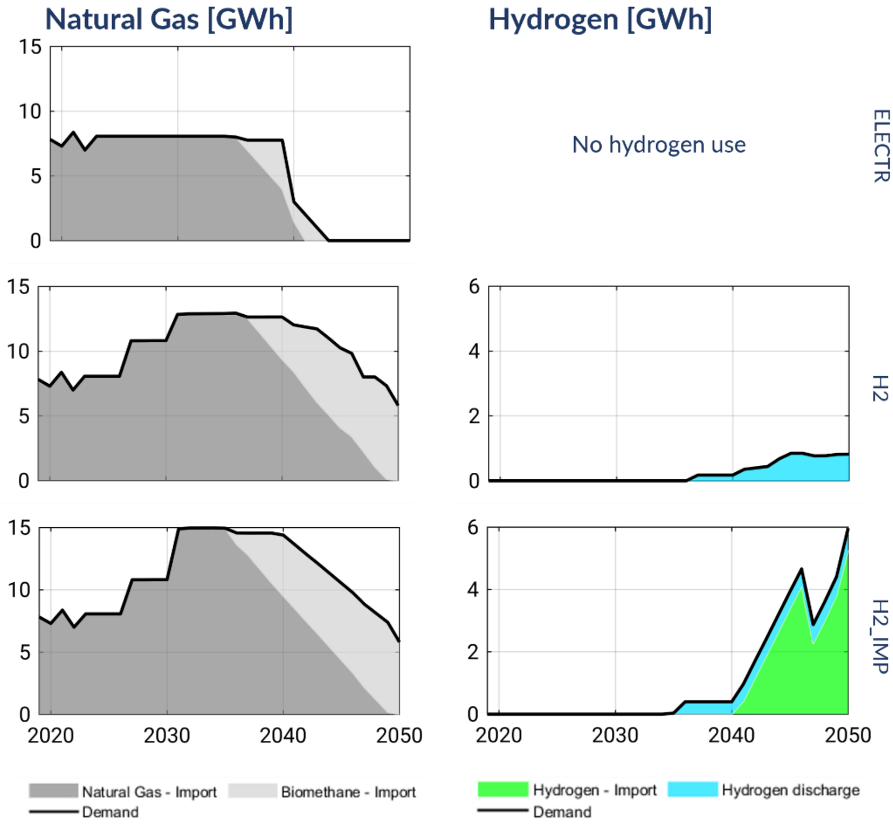


Figure 17 - Consumption of natural gas, biomethane and hydrogen at Torino Airport in the three technological pathways under the Ambitious *decarbonisation targets.*

Fuel cell blend. Figure 18 reports the composition of the fuel cell blend for the two hydrogen-based scenarios in milestone years. At the beginning, the fuel cell would be entirely fed with natural gas, as this allows to reduce the operational costs of the system without missing on environmental targets. In 2040, the fuel cell would still be fed with natural gas for a significant share (from 60% to 70%), but the purchase of biomethane would be needed in other to remain compliant with emissions reduction objectives. Modest production of hydrogen would also begin in the same period. In 2050, the challenging environmental targets would require the total greening of the blend. In the *H2* pathway this is mostly achieved through biomethane, in the *H2_IMP* one with imported hydrogen. On-site production of hydrogen contributes to a smaller extent to the greening (25% and 12%). The choice of biomethane over hydrogen, or vice versa, would be clearly determined by the price of the supply and availability of the infrastructure. However, it seems clear that an external supply of alternative fuels is needed for the operation of the fuel cell in the long-term.

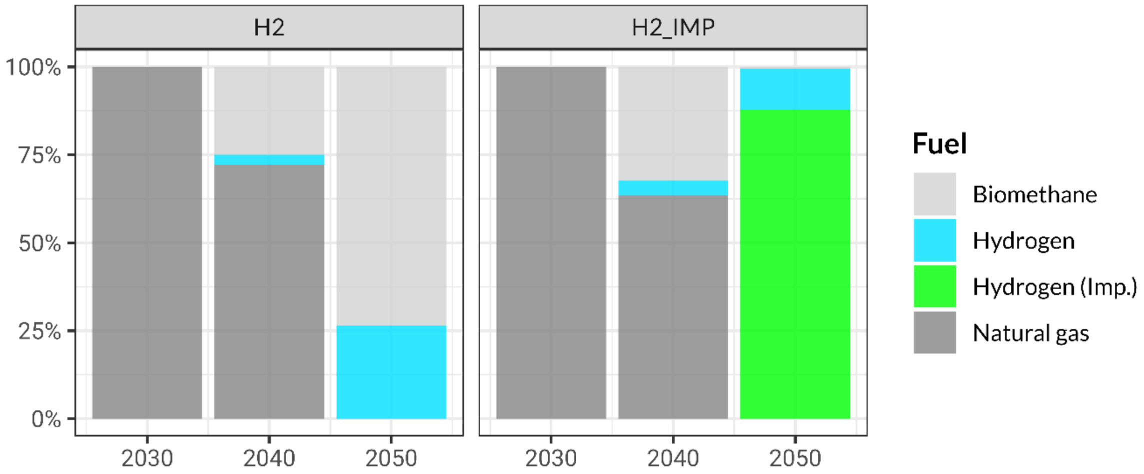


Figure 18 - Composition of the fuel cell blend in hydrogen-based scenarios for Torino Airport.

Grid dependency. All the technological pathways imply a dramatic reduction of the dependency of the airport on the grid for its electricity needs. From the current 100%, in 2040 the dependency falls to 50% (*ELCTR*), 38% (*H2*) and 26% (*H2_IMP*) respectively. In 2050 the dependency increases slightly, both because of the additional demand for the electrification of heating and for the decommissioning of part of the fuel cells capacity.

Although the dependency on the grid is lower for hydrogen-based pathways, it should be underlined that in these cases the dependency is shifted to biomethane/hydrogen imports, to a comparable extent with respect to the present utilisation of the natural gas grid (Figure 19). Overall, all the pathways would reduce the dependency of the airport from imports, strengthening its resilience to fluctuation of energy prices. However, the autarchic sustenance of the airport energy system seems unlikely, with the imports of both electricity and alternative fuels still being a significant part of its economy and providing a valuable contribution to decarbonisation.

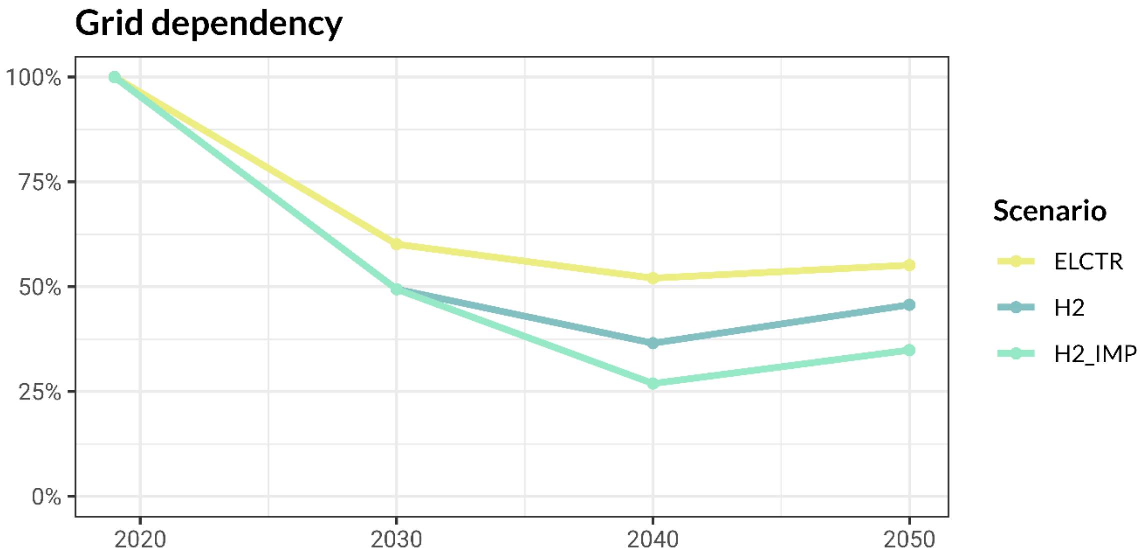


Figure 19 - Dependency on the electricity grid for the three technological pathways (Torino Airport).

<u>The costs of transition</u>. Finally, the costs of the transition are evaluated. It should be stressed that these costs should not be taken as reference of a realistic transition pathways., as they strongly rely on scenario assumptions on future trends in energy and technology markets which are difficult to predict and lead to major uncertainties. The system costs are only shown to compare the trends in alternative technological pathways.

Figure 20 and Figure 21 show the average annual OPEX and the total period CAPEX for the three technological pathways. First of all, it is noted how, compared to a *No Action* scenario in which all the energy is purchased from external sources, the self-production regime allows to abate the OPEX of the airport, in all scenarios. Hydrogen-based pathways perform slightly better than the *ELCTR* one. Savings are higher by 5% and 10% for the *H2* and *H2_IMP* pathways in the 2031-2040 period. The difference increases towards 2050 because, despite the more costly fuels needed to reduce the environmental impact of the fuel cell, in the *ELCTR* pathway the expenses increase to purchase the electricity needed for the electrification of the heating sector. The high fixed costs of the fuel cells are effectively counterbalanced by the sales of energy efficiency certificates in the first years of operation, reducing the OPEX of the CCHP system.

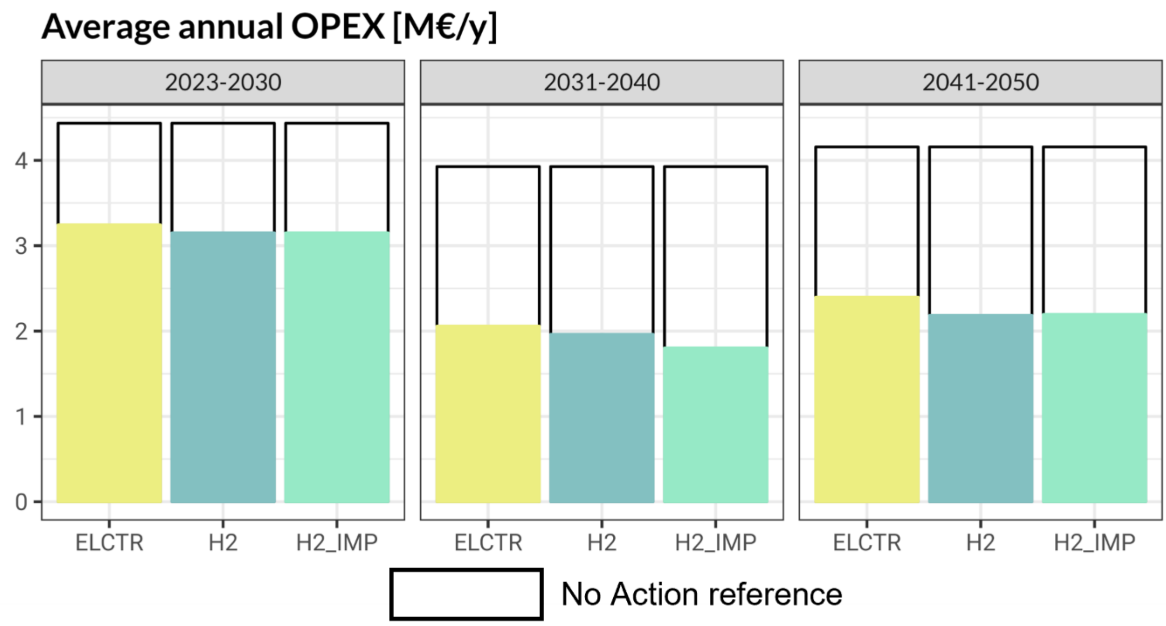


Figure 20. Operational expenditures needed for the realisation of the transition pathways under the Ambitious *decarbonisation target (Torino Airport).*

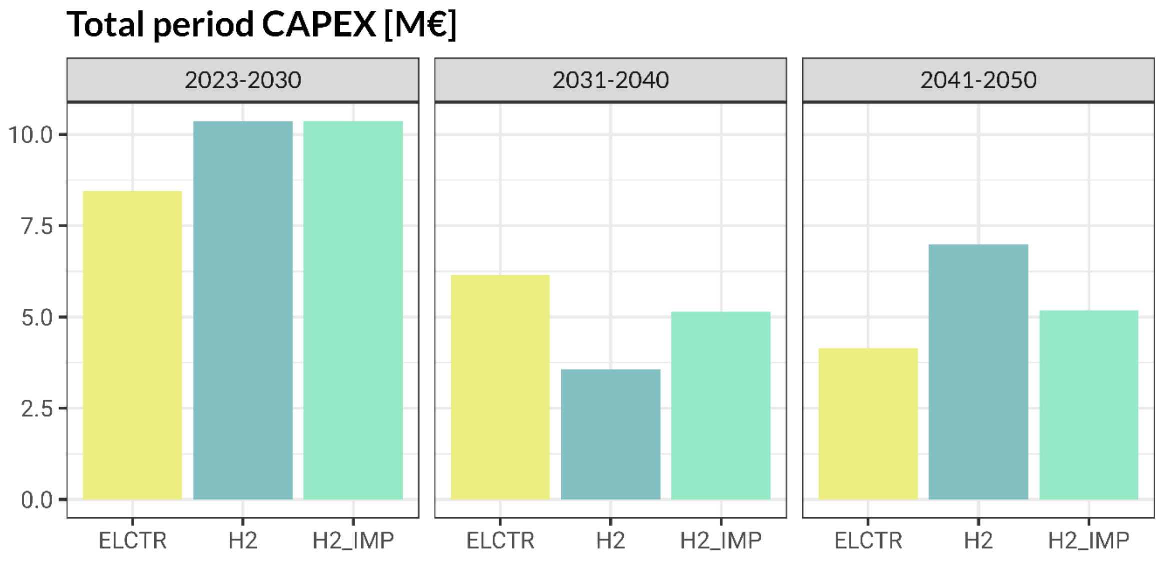


Figure 21 - Capital expenditures needed for the realisation of the transition pathways under the Ambitious *decarbonisation target (Torino Airport).*

For all the pathways, significant CAPEX are required in the 2023-2030 period, where the bulk of the PV capacity is built. For the *ELCTR* pathway, another major CAPEX effort would be needed in the successive period, to build enough battery storage capacity. Throughout the period, higher CAPEX would be required to realise the hydrogen-based pathways, due to the high initial cost of the fuel cell and electrolyser and despite the foreseen reduction. In particular, high costs can be expected at the turn of 2040, in order to build electrolyser capacity.

Overall, an imbalance between the OPEX of the airport and the CAPEX needed to realise the transition can be observed. OPEX makes up most of the airport's expenses, so that it results economically convenient to invest in high-CAPEX technologies, even with a relatively high payback time, because of the economic savings which can be achieved in the long-term on the purchase of energy.

4.4.1.3 Accelerated decarbonisation objectives

This section compares the efforts needed to accelerate the decarbonisation objectives with respect to the *Ambitious* scenario for the three technological pathways.

Emissions. As could be expected from the discussion in the previous section, significant differences can be observed in the accelerated trajectories. These are reported in Figure 22 and Figure 23 and compared to a *No Action* case, in which the only contribution to emissions reduction is brought by the decarbonisation of the electricity grid. For the *ELCTR*, the *Accelerated* target was almost achieved without the need to impose a decarbonisation trajectory, so that minor changes are needed. This confirms the synergy between environmentally and economically advantageous choices in this pathway. Conversely, for hydrogen-based pathways a significant modification of the trajectory is needed in order to meet the target, hinting to major changes in the configuration of the energy.

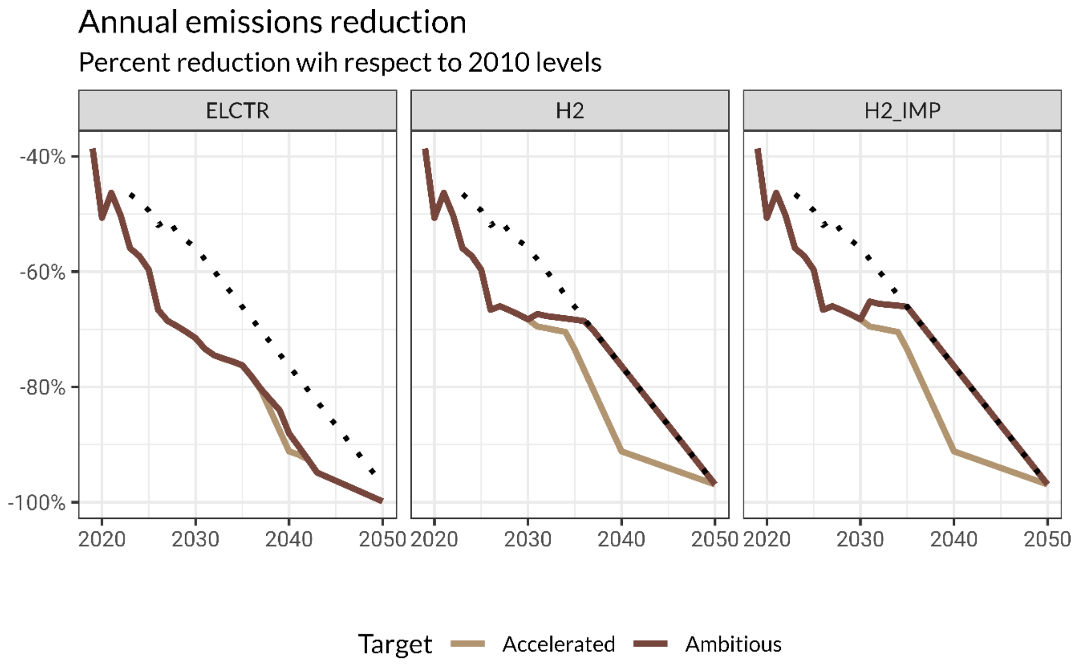


Figure 22 - Emissions reduction trajectories in Ambitious *and* Accelerated *scenarios. Emission trajectories of the three technological pathways are compared with respect to a* No Action *case in which all the energy is purchased from external sources, and the only mean of reducing emissions is though the decarbonisation of the grid.*

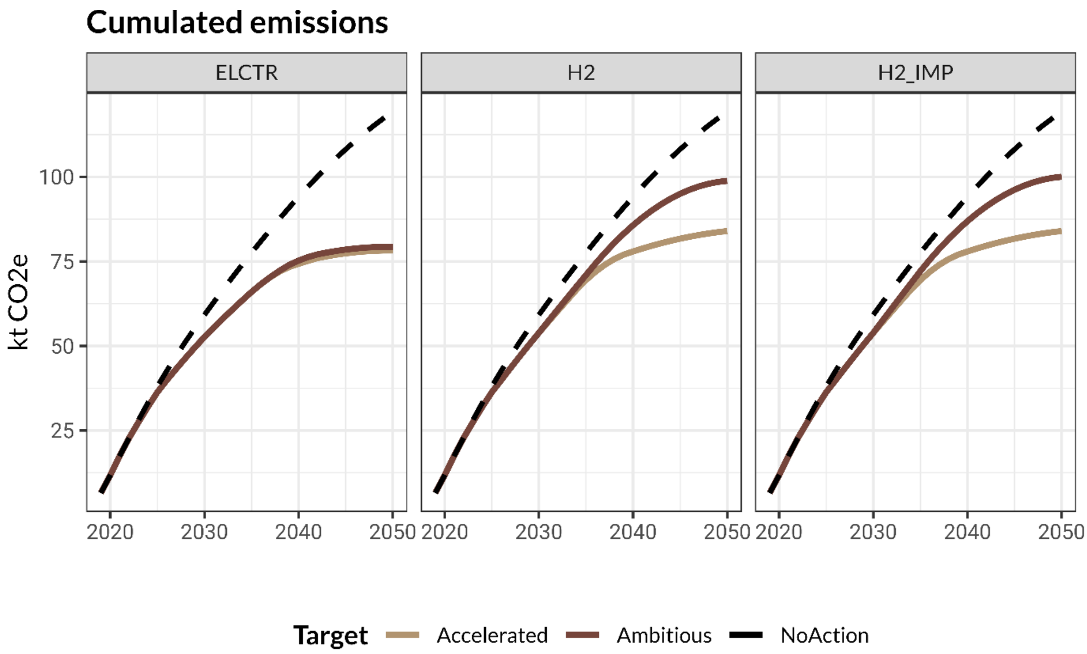


Figure 23 - Cumulative emissions in Ambitious *and* Accelerated *scenarios. Cumulative emissions of the three technological pathways are compared with respect to a* No Action *case in which all the energy is purchased from external sources, and the only mean of reducing emissions is though the decarbonisation of the grid.*

Accelerating the environmental targets at 2040 has a non-negligible effect on the cumulated emissions at the end of the period for hydrogen-based pathways, which move from almost 100

$ktCO_{2e}$ to less than $85\ ktCO_{2e}$. However, the *ELCTR* pathway, compatibly with its steeper emissions reduction trajectory, lead to even smaller cumulative emissions (about $75\ ktCO_{2e}$).

Fuel cell size reduction. One key difference between the *Ambitious* and *Accelerated* targets for hydrogen-based pathways is the reduction of the size of the fuel cell, which is limited, even in the case with external hydrogen supply to $0.25\ MW_e$. This because the decarbonisation of the blend of a large fuel cell would be excessively costly before 2040, having to rely on large-scale on-site production or significant purchases of biomethane for a prolonged period, so limiting the economic benefits of cogeneration.

Electrification rate. One other measure needed to accelerate the airport's targets is the electrification of heating Figure 24. Also in the *ELCTR* pathway, a slight acceleration of this measure is required before 2040. In the hydrogen-based pathways the changes is more remarkable, with heat pumps moving from about 25% of generation for the *Ambitious* target to more than 60% in case of acceleration.

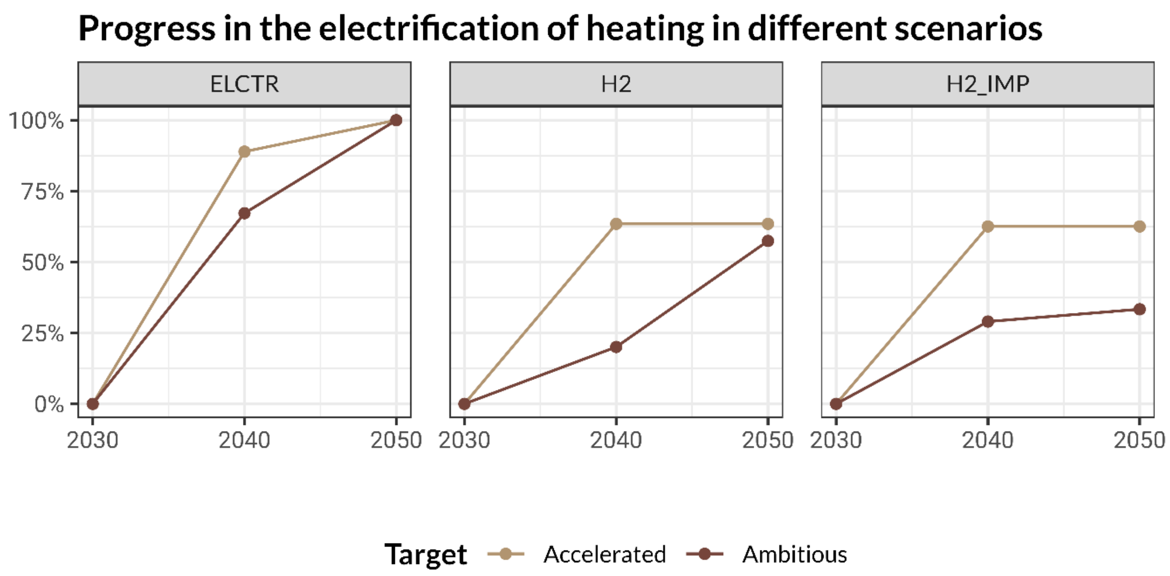


Figure 24 - Progress in electrification of heating in the Ambitious *and* Accelerated *decarbonisation targets for Torino Airport.*

Natural gas mix. Another significant measure needed to achieve the accelerated decarbonisation targets is the additional purchase of biomethane Figure 25. As said for electrification of heating, also in the *ELCTR* pathway a minor increase in the share of biomethane is needed in order to support the 2040 target. However, the difference is stark for hydrogen-based pathways, which not only see a decrease of natural gas demand because of a more pronounced electrification of heating and reduction of the fuel cell size, but also requires the purchase of nearly 100% of biomethane in their gas mix by 2040.

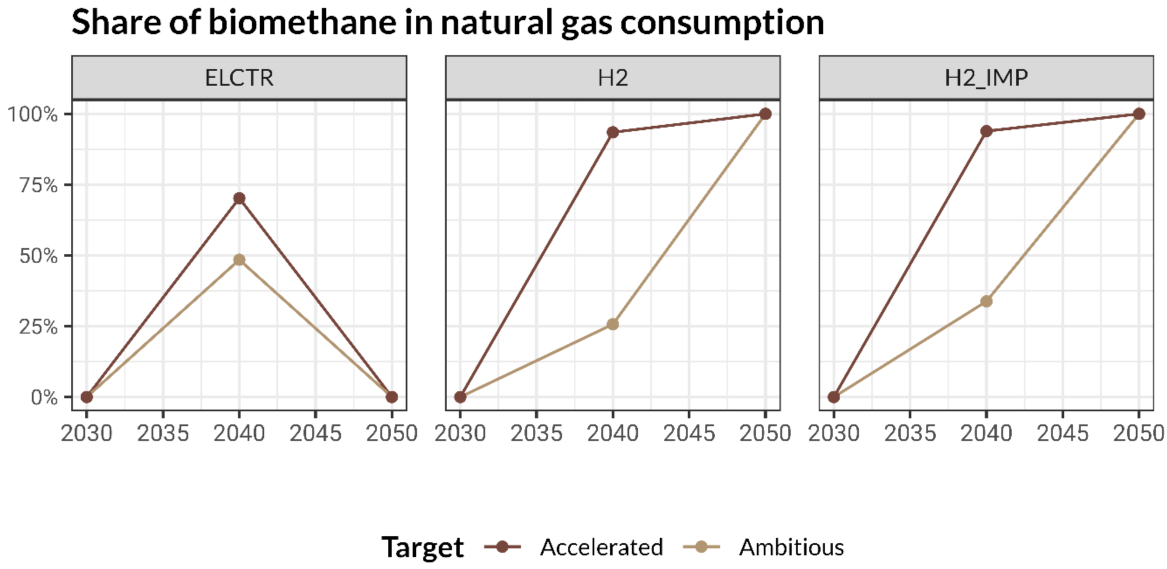


Figure 25 – Share of biomethane in the purchase of natural gas in the Ambitious *and* Accelerated *target (Torino Airport).*

Costs of accelerated transition. The costs of the system does not see major variations for the *ELCTR* pathway in case of an acceleration of the decarbonisation targets. The differences are more evident for hydrogen-based pathways, which see an increase of the CAPEX in the 2031-2040 period, despite the reduction of the size of the fuel cell, because large investments in electrification are needed. However, investment expenditures are lower in the 2041-2050, since the purchase of technology is anticipated. Overall, the total CAPEX required for the transition remain the same, although this is valid under the assumption made on the rapid decrease of all hydrogen related technologies, shortly after 2030. If this were not to occur, overall costs of the system would be higher in the accelerated pathway. (Figure 26).

Also the OPEX would increases for hydrogen-based scenarios throughout the 2031-2050 period, mainly because of the reduced size of the fuel cell and the increased share of biomethane in the gas mix.

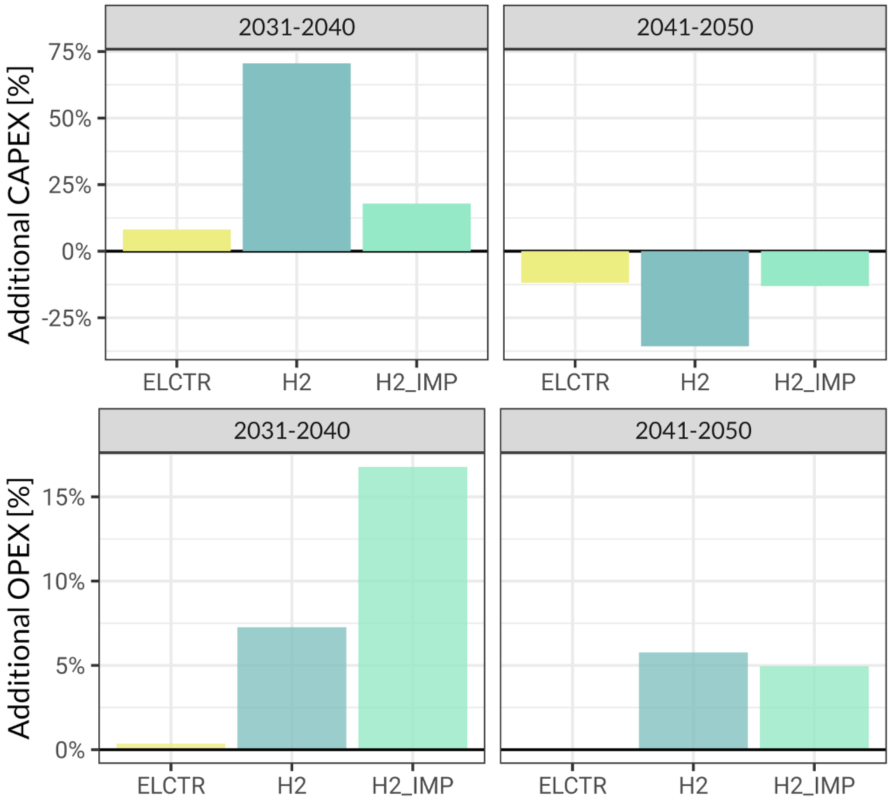


Figure 26 – Additional CAPEX and OPEX needed to Accelerated *decarbonisation targets for Torino Airport in the three technological pathways.*

4.4.2 Evaluation of modelling results

First of all, some general considerations can be made on the different clusters of measures: in particular there are measures that achieve both the goal to improve the economics of the system and the overall emissions, and there are measures that can be considered by the model a good intervention on the economic side but that when stressing the environmental targets are not able to fulfil the requirement set. This highlights as sometimes the options selected have a good effect on the economics but imply a downside on the environment: in particular this is quite evident with the installation of the FC system, that implies an higher efficiency and thus positive cash flows but at the same time moves the energy demand from the electrical side to the thermal side increasing the demand of natural gas and then requiring to decarbonise the fuel inlet through options that are more expensive and complex to put in place if compared to electricity decarbonisation.

Other general considerations can be made on capital costs and their impact on general costs associated to energy: in the period considered the ratio between CAPEX and OPEX is quite similar in the different scenarios examined and the OPEX weights from three to four times the CAPEX required.

It is interesting to underline that while the no action scenario would allow to achieve in any case good results in terms of decarbonisation (-80% if compared to baseline year) thanks to the decarbonisation of the grid, from an economic standpoint the scenarios with actions allow to reach important savings on the overall period (about 10%).

Generally speaking, accelerating the environmental targets did not have a strong impact on the total amount of CAPEX in our analysis, but only anticipated them on the time scale. Anyway, it should be underlined that this consideration would be challenged if the assumed decrease of investment costs of hydrogen-related technologies right after 2030 should not take place.

For what concerns the electrical scenario, the solutions proposed are quite flexible to the anticipation of targets: investments and carbon trajectories are quite overlapping and to reach targets faster the two solutions that are enhanced and anticipated in time are the use of biomethane and the electrification of the thermal demand.

On the other hand, for the hydrogen-based scenarios, due to the conflictual impact of the installation of SOFC fuel cells we have two effects: anticipating the environmental target implies a strong reduction of size of the system and an earlier implementation of the electrification on thermal demand conjugated with the purchase of biomethane and later on of green hydrogen. A single FC is still affordable by the system thanks to the use greener fuels, but this scenario appears to be very sensitive to more challenging commitments.

For what concerns the use of hydrogen, its impact is negligible before 2040 also due to the supposed costs of technologies: these options require, due to the low overall transformation efficiency, high CAPEX related to electrolysers, PV systems and infrastructure necessary to feed the plant. On the other hand, the upside is related to an enhanced grid independency if compared to other scenarios.

Generally speaking for all the scenarios, the electrification appears to be a necessary driver, independently from the availability of hydrogen in the system.

Another common remark that can be made is related to the fact that anticipating the commitment implies a more relevant role of the environmental constraint on the economical one.

In conclusion the electrification of thermal needs conjugated with the local production of electricity with photovoltaic plants in combination with batteries to store the excess production during peak hours is the most preferable choice, and the technologies that allow to enhance faster the decarbonisation are the earlier electrification of the thermal demand and the purchase of biomethane.

4.4.3 Robust smart energy hub concepts

The modelling activities conducted in this study allow to draw several insights on the definition of a robust energy strategy for Torino Airport. The following cornerstones of the development of the airport were identified:

1. **Increased self-sufficiency.** Independently on the chosen technological pathway, a radical shift of the airport from the current *energy consumer* to *energy producer* role should be a pivotal part of the energy strategy. This would bring benefits under both the economic and environmental aspects. As a large energy consumer, the overwhelming operational expenditures of the airport justify the investment in high-cost technologies for on-site energy generation. Moreover, the reduced dependency on energy imports would mitigate the adverse effects of future energy crises and market fluctuations. On the environmental side, significant emission savings can be achieved through on-site renewable generation and highly efficient cogeneration, although the environmental convenience of the latter will depend on the availability of *green energy supplies* (see the third cornerstone). Conversely, building significant renewable PV capacity should be a priority for any technological pathway. Significant storage capacity should be installed in order to address the mismatch between demand and renewable supply, with batteries generally favoured over hydrogen systems, due to the higher roundtrip efficiency. However, it would be excessively expensive to store all the excess renewable generation on-site, so the bi-directional exchange of electricity with the utility grid will remain an important tool to increase the penetration of renewable generation at the airport.
2. **Diversification of resources and sector coupling.** Another constant of each strategy investigated lies in the increased complexity of the energy system. Under the current configuration of the airport, different energy sectors are compartmentalised and associated with specific energy carriers. This is going to change as the airport transition to a sustainable, integrated energy system. The consumption of fossil fuels should be flanked and eventually replaced with drop-in, renewable alternatives, such as HVO and biomethane. The operation of conventional boilers fed with renewable fuels can support the decarbonisation of the heating sector in the medium term, as electrification of heating gradually gains momentum. In the long-term, the share of heating covered by electric heat pumps is projected to increase, determining a significant increase of electricity demand. Alternatively, a mix of electrification, conventional gas boilers fuelled by biomethane, and cogeneration represent a valid solution to achieve net-zero targets while mitigating the increase in electricity demand. Electrification becomes particularly appealing in conjunction with the on-site provision of low-carbon and low-cost electricity through PV, batteries and fuel cells.

3. **Need for green energy supplies.** As stressed above, increasing the self-sufficiency of the airport should be one of the cornerstones of any energy strategy. Nevertheless, the analysis revealed that the realisation of an energetically autarchic system would be hard to achieve from an economic perspective. Large fuel cell capacity would allow to cover a significant electricity baseload, but the capability of the airport to sustain fuel cells operation through on-site hydrogen production is limited by the limited space available for PV installation. Therefore, the dependency on gaseous imports would increase. When considering technological pathways without fuel cells, the dependency on gaseous imports is minimised, but the reliance on grid electricity is higher, especially in view of increased electricity demand determined by the full electrification of the heating sector. It is therefore clear that, independently on the energy strategy selected, the airport will still need to access significant quantities of green energy carriers from external sources. Under this perspective, the strategy of the airport will still need to rely on the national electricity grid and its foreseen decarbonisation. Moreover, external supplies of green gases, either biomethane or hydrogen, represent a fundamental enabler of a strategy based on fuel cells. Accordingly, the development of these markets represents a major source of uncertainty for a strategy based on fuel cells.
4. **Integration in local hydrogen economy.** Hydrogen, as a particular instance of external energy supply, is worth a separate discussion. Contrarily to biomethane, the supply of hydrogen from external sources will require the establishment of a dedicated infrastructure connecting the airport to hydrogen producers. If these producers were located far from the airport, the cost required to transport hydrogen would soon cancel out the economic feasibility of an energy strategy based on fuel cells. Moreover, the volume of hydrogen required by the airport for power generation purposes alone would likely be too small to justify significant investments in transport infrastructures over long distances. In order to secure a supply of hydrogen at an affordable price, a concerted effort of the airport with local stakeholders towards the realisation of a local hydrogen economy would be needed. Moreover, other possible uses of hydrogen at the airport, such as for GSE operations, should be evaluated in future studies.

Based on the four cornerstones delineated above, two alternative concepts defining a *robust energy hub* for Torino Airport are presented in Figure 27 and Figure 28.

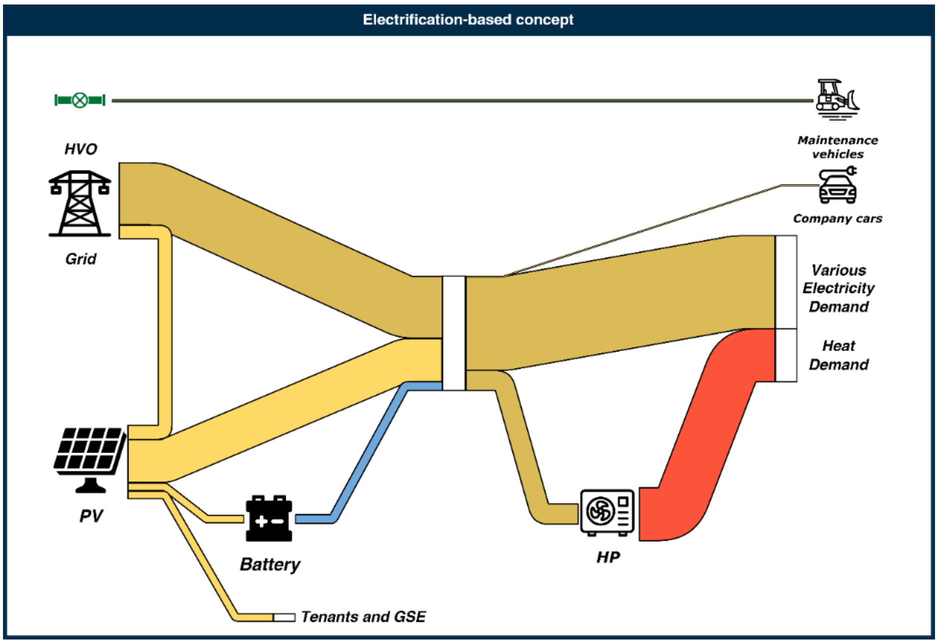


Figure 27 - Electrification-based robust energy system concept for Torino Airport.

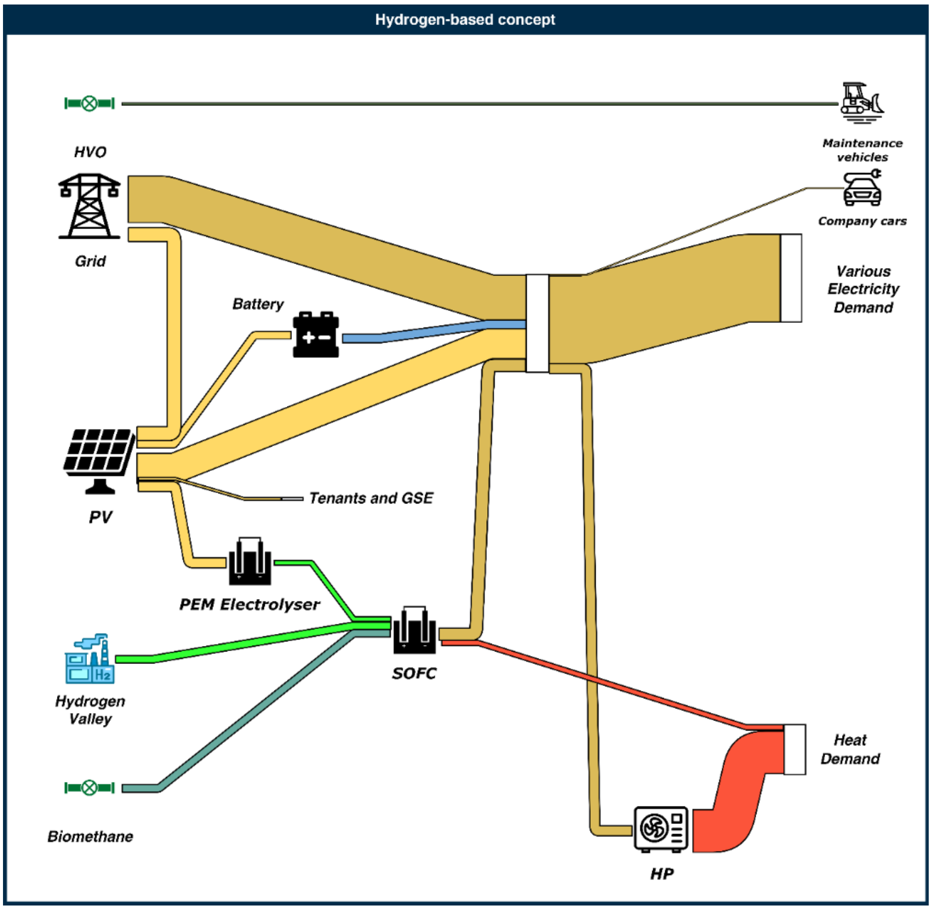


Figure 28 - Hydrogen-based robust energy system concept for Torino Airport.

4.5 Conclusion

The creation of the airport energy model made it possible to see concisely what the main sources of primary energy are and to evaluate their impacts in terms of emissions: this allowed in first instance to make an assessment of the nature of the energy loads present, their contemporaneity and their potential for optimization.

Next came the analysis and introduction of the drivers that can influence energy demand in order to model its response over time according to variations in the inputs that can be predicted.

We then moved on to the analysis and modelling of the different technological options available to the model, options useful for the subsequent optimization of system emissions and costs.

Consequently, the model was made to work as an optimizer by exploiting its potential in terms of data processing, assigning it different objectives from time to time: first by simply optimizing costs, then by inserting environmental constraints, and then by stressing its impact with the anticipation of constraints over time.

This made it possible to analyse different scenarios based on antagonistic and complementary technologies, and to identify the "no regret" solutions that underpin the construction of a solid and robust strategy over time.

In particular, it emerged that for the size of the airport considered and the energy conformation of the geographic area in which it is located, electrification of demand coupled with significant on-site renewable production is the most effective and resilient way to achieve the goals set.

As of today, this scenario is preferable to the introduction of hydrogen also because of the nature of the airport demand, which is highly shifted to electric, allowing for a smoother decarbonisation by basing the strategy on a more flexible and easy-to-manage carrier such as electricity. The role of hydrogen appears to be assessable after the ‘40s, where, however, the unknowns related to cost and efficiency of the technology to date are difficult to assess. It also emerges that for this case study, energy storage through batteries is more competitive than chemical storage thanks to the lower plant complexity to be addressed in addition to the higher overall efficiency of the system, with lower associated energy losses.

In any case, the basis on which to build the strategy turns out to be energy efficiency, which makes it possible to reduce the primary energy input to the system and which therefore turns out to be the most direct source of decarbonisation, in continuity with the path undertaken by the airport for several years already.

Along with this fundamental pillar, other technological choices must be made to decarbonize energy sources: in particular, the most cost-effective choice from both an economic and environmental point of view turns out to be the self-production of energy through renewable sources and its storage through batteries to enable the airport's production and load curves to be as close as possible.

In addition to the electrification of other residual uses associated to internal transport, the other key technological choice for moving toward Net Zero and accelerating the achievement of environmental goals turns out to be the electrification of thermal generation through heat pumps in parallel with the purchase of biomethane.

In this sense, vital will be the evolution of these two options over time, both from an economic (and thus price) and availability (particularly for biomethane) point of view. The reliability of these options would be even more crucial in scenarios based on the presence of hydrogen and stationary production, being more based on the decarbonisation of fuels entering the airport.

The analysis also shows that anticipating decarbonisation targets does not have so much considerable impact on the amount of CAPEX involved as on their distribution over time. The scenario with pure electrification in this sense turns out to be much more flexible, not entailing radically different technological choices thanks to the fact that the interventions proposed by the model have a positive impact in economic terms even before environmental ones. This will of course depend on the rapidity with which emerging technology markets will develop.

Finally, one consideration regarding the installation of a 250 kW Fuel Cell: such an intervention remains feasible even with ambitious environmental goals. However, its introduction increases dependence on instruments such as biomethane and green hydrogen whose future availability and price are difficult to predict at present. Achieving the same goal would also require considerable complication of the system compared to the electrification-only scenario.

Key uncertainties remain to be assessed. In particular, the availability of external hydrogen and biomethane supply at different price levels should be further investigated. In particular, different hydrogen supply value chains should be investigated in detail. Moreover, a sensitivity to energy price variations should be accompanied to the conservative price level scenario considered in this study. Finally, the effect of a slower market growth of hydrogen-related technologies on hydrogen-based scenarios should be investigated.

5 Stavanger Airport – scenario study and system design concepts

5.1 Methodology

5.1.1 Methodological framework used for the scenario analysis

Continuous and regular contacts were maintained between Avinor and SINTEF throughout the study. A dedicated workshop was organised in May 2022 and apart from SINTEF included representatives from the management and operational personnel at the airport. SINTEF participated in several meetings between Stavanger airport and potential supplier of biogas, developer of dedicated EMS systems (internal project) and vendor of chargers for electric aircrafts. In addition to this, the study utilised knowledge and learnings from several previous projects and technical studies for deployment of new technologies at the airport.

5.1.2 Models and other tooling

SINTEF Energi applies "Integrate" [36] (formerly eTransport), a software system for the optimisation of integrated energy systems. It can be used to optimise the development of an energy system while considering the projections in energy demand and the different technological possibilities for energy supply, conversion between energy carriers, distribution, storage, endues measures and restrictions on CO2 emissions [37].

The Integrate model minimises total energy system cost of meeting predefined energy demands of electricity, space heating and tap water heating within a geographical area over a given planning horizon. The model includes alternative supply infrastructures for multiple energy carriers: electricity, natural gas, liquid natural gas (LNG), oil, biomass/waste and district heating. The novelty of Integrate is that all physical components and geographical topology for different energy infrastructures are included in one single optimisation model for the whole energy system within the given area [36]. Geographical details like transmission distances and alternative locations are accounted for, and the competition between different energy types is implicitly handled by the algorithm. The actual physical components in the studied energy system and the energy flow between these components are modelled explicitly.

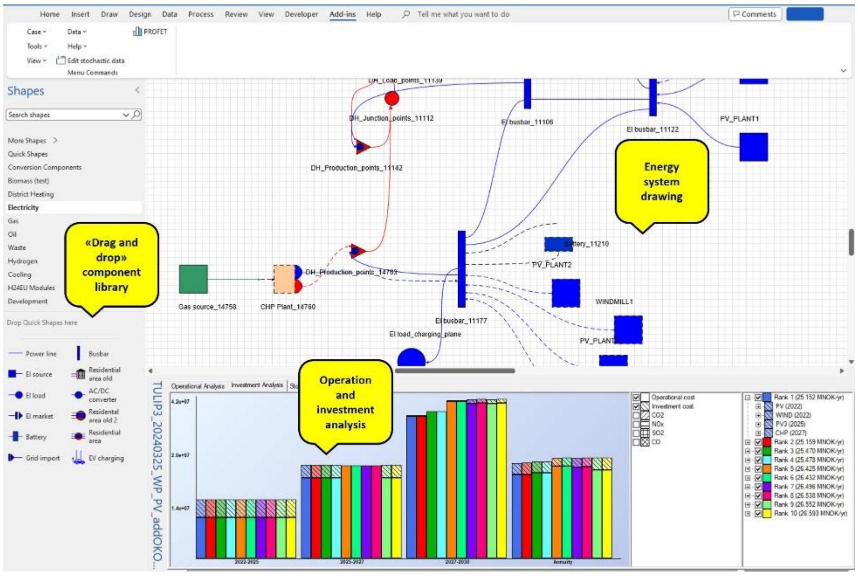


Figure 1 Interface for Integrate tool

Integrate is separated into an operational model (energy system model) and an investment model (see Figure 1). In the operational model, there are component libraries with sub-models for each energy carrier and for conversion components [36]. The dataset for the particular case defines the specific characteristics of the involved components. The operational planning horizon is relatively short (1–3 days) and the model solution finds the cost-minimising operation for a given infrastructure and for given energy loads. The typical time-step in the operational model is 1 hour, and this is not feasible for investment analysis where the planning period can be over 20 years. Therefore, the operational analysis is separated from the investment analysis, and annual operating costs for different energy system designs are pre-calculated by solving the operational model repeatedly for different seasons (e.g. peak load, low load, intermediate, etc.), periods (e.g. 5-year intervals) and relevant system designs (states). Annual operating and environmental costs for different periods and energy system designs are sent to the investment model that finds the investment plan that minimises the present value of all costs over the planning horizon.

The solution methodology is a combination of Linear Programming (LP) and Dynamic Programming (DP/SDP) (see Figure 2). The result from the model is a cost-effective development plan, as well as a model of the operation of the system hour by hour in different seasons. Integrate is used to study local energy systems, such as a housing association or a district. There is also an associated model for the entire European energy system: Integrate Europe. Modularity allows to introduce new components, which can be very specific, and refine the existing, but the model does not consider physical constraints (e.g., congestions or/and voltage violations in electric grid).

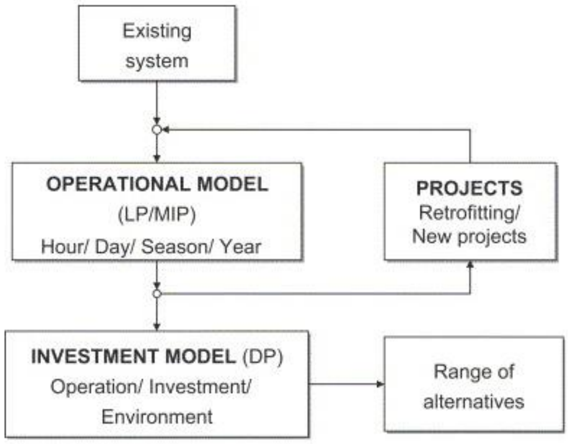


Figure 2 General structure of Integrate. Source: [36]

Integrate requires spatial data (e.g., system borders, location of system components), time aspects (planning horizon), energy needs, existing energy supply, energy prices and possible investment options. Main features of the tool include:

- Modular structure includes components for a variety of energy vectors e.g. electricity, district heating, hydrogen and corresponding components for energy generation, consumption and conversion
- Visual representation of input and output (GUI)
- Calculates the optimal expansion plan, e.g., next 50 years
- Operational optimization with hourly resolution
- Considers that different energy carriers both compete and can be complementary.

As output, Integrate provides one or more expansion plans in ranked order along with the operation of the system for the defined representative days. Integrate can thus optimize the expansion planning of the local energy system by considering an existing system configuration.

5.1.3 Process, timeline and milestones

The process workflow in the activity included several steps as presented in Figure 3

- **Scenarios:** Avinor and more specifically Stavanger airport have been involved in several national research and innovation projects related to the energy sector. This allowed the project group to rely on outcomes from these projects, as for example, results and conclusions from the previously mentioned Elnett21 project have been used as basis for creation of target scenario both in terms of the anticipated growth of electricity demand and selection of the alternative solutions. In addition, knowledge, and experiences from other airport cases in TULIPS, which were exchanged via dedicated workshops were an important inspiration for the study.

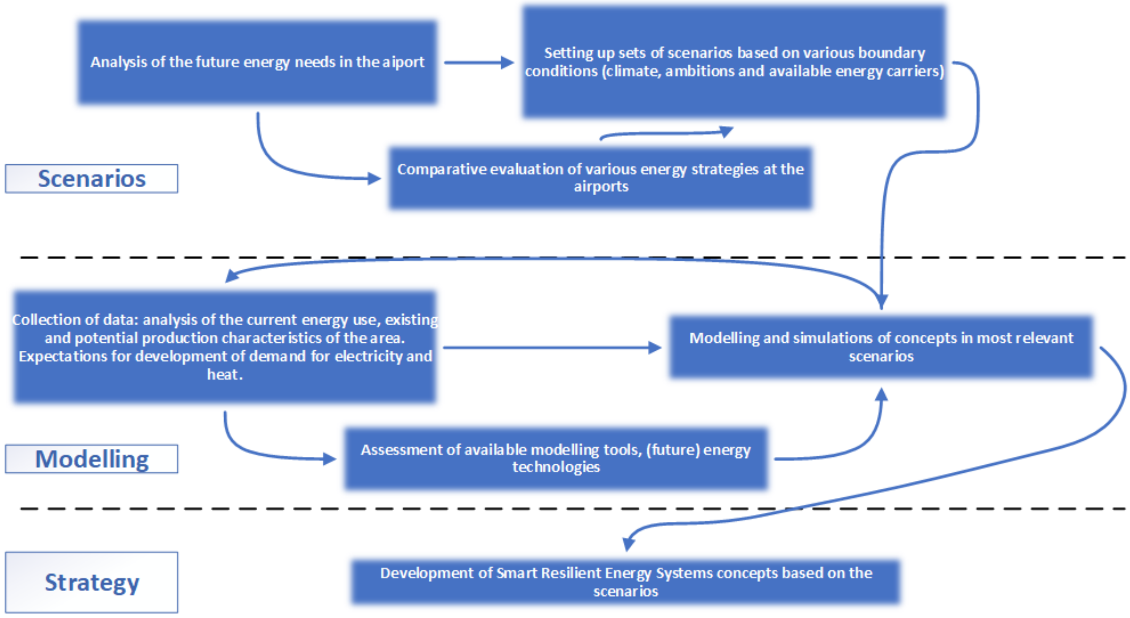


Figure 3 Workflow in the Norwegian case.

- **Modelling:** Several previous screening studies done by Avinor were used as reference for investment costs for different technologies. Still collection of data and its introduction into the model has been the most time-consuming and demanding part, requiring several iterations between collection and modelling parts.
- **Strategy:** The modelling results in Integrate present several compositions of different investment options, which are ranked according to their operational and investment costs. The results provide a quantitative input to development of the resilient future strategies.

5.2 Scenarios and solution pathways

5.2.1 Introduction to the airport energy system

The existing configuration of the energy system at Stavanger airport is presented in Figure 4 in simplified form.

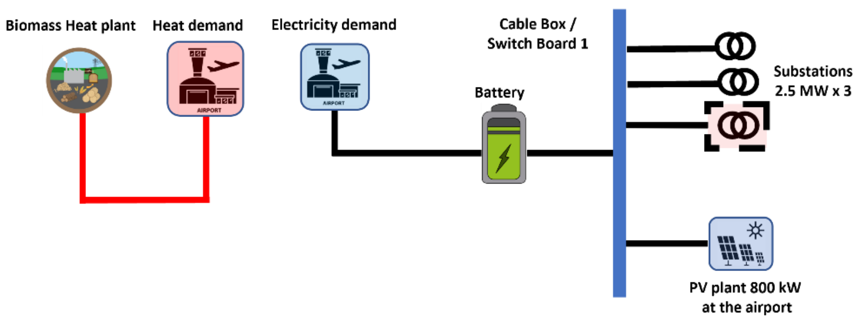


Figure 4 The present connection diagram at Stavanger airport (simplified).

The airport receives:

- Electricity from the conventional grid (fed by 2x2.5 MW transformers with one in reserve)
- Local PV generation (880 kWp in total, producing between 0.8-0.9 GWh pr. year
- Biomass-fired local district heating using shaved wood (max 4 MW of capacity).
- 560 kW Battery Energy Storage System (BESS) for peak shaving and storing excess energy from PV.

Development of the energy mix during the recent years is presented in Figure 5.

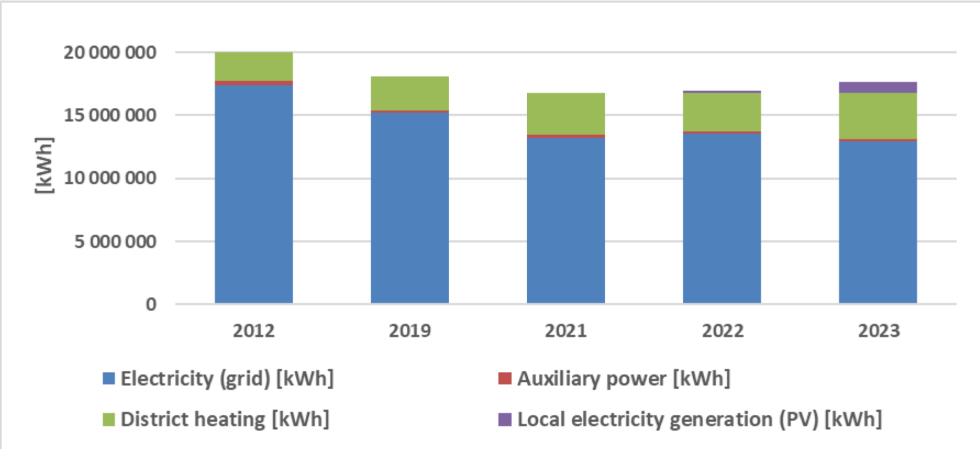


Figure 5 Energy mix at Stavanger airport Sola. Source: [31]

The figure shows gradual introduction of local electricity generation from PVs, which starts in 2022 and in 2023 reaches app. 5 % of the total energy consumption. It is also necessary to remind that district heating (20% of the total consumption in 2023), used by the airport, is fired by biomass and thus is also renewable.

Conventional electricity supply (grid)

As it appears from Figure 1, the main share of the energy demand is electricity, which is delivered through the conventional power grid (see Figure 6). The two main connections of Stavanger airport Sola to the grid are at 15 kV level, realised via 15/50 kV transformer connecting the high voltage distribution and regional grids (the so-called Solaringen). The latter is connected to the transmission (300 kV) grid.

At present the substation capacity at the airport is 7.5 MW. It is feed by 3 transformers of 2.5 MW capacity. The primary feed is by two transformers with total capacity of 5 MW. The third one is a backup transformer.

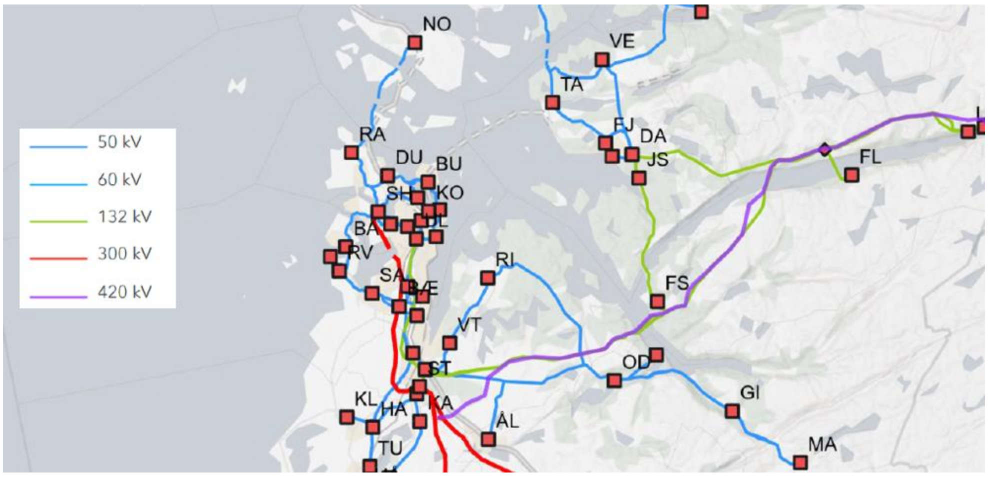


Figure 6 Power grid surrounding Stavanger airport Sola. Source: [38]

According to a recent assessment of power grid in Rogaland, the area around Stavanger airport will require grid improvement in few years due to gradually increasing electricity demand and limited available capacity in the regional grid and transformer stations.

Figure 7 Indication of the capacity available in the regional grid (yellow = limited). Source: [38].

Several improvement alternatives are discussed, including increase of the voltages in the surrounding grid and construction of the new lines and cables. These improvements are very costly projects and lay outside scope of the present project. More interesting is suggestion for Stavanger airport to keep the existing grid configuration but employ local electricity generation and flexible resources to match the forthcoming increase in the energy demand.

Electricity from the local PV units

In 2022 the airport installed 1 780 bifacial PV panels with total capacity of 880 kWp. Production in 2023 was 856 000 kWh (see Figure 5), which is 60 000 more than expected. The operational experience so far was very positive: the panels do not require any specific maintenance except trimming of the vegetation nearby.

Figure 8 Solar panels at Stavanger airport (2022).

The installation successfully sustained the heavy winds (up to 42 m/s) in 2023 without any damages. It is also necessary to mention that the total available area at the airport allows installation of app. 20 MWp of PVs.

District heating (biomass)

The airport does not use district heating in its common meaning, but rather decentralised waterborne heat supply. The heat energy is provided from the local heating plant, which uses biomass i.e. shaved wood.

Figure 9 Biomass-fired district heating. Source: Avinor.

The airport does not own the plant but purchases heat supply as service. The plant was established in 2011 providing 2 MW and was expanded with 4 MW in 2022. The energy is used for space heating of the terminals and surrounding buildings, in addition it is also used for de-icing of parking slots for airplanes near the gates.

5.2.2 Energy system key performance indicators.

Norway is a part of the Nordic power system (ex-NORDEL) and has traditionally had very low electricity prices, compared to the continental Europe. The situation has been gradually changing during the recent years, when several new connections to the continent were opened, especially the recent (2022-09-10) connections of 1 400 MW to the UK (North Sea Link) and Germany (2021-03-31) 1 400 MW (NordLink).

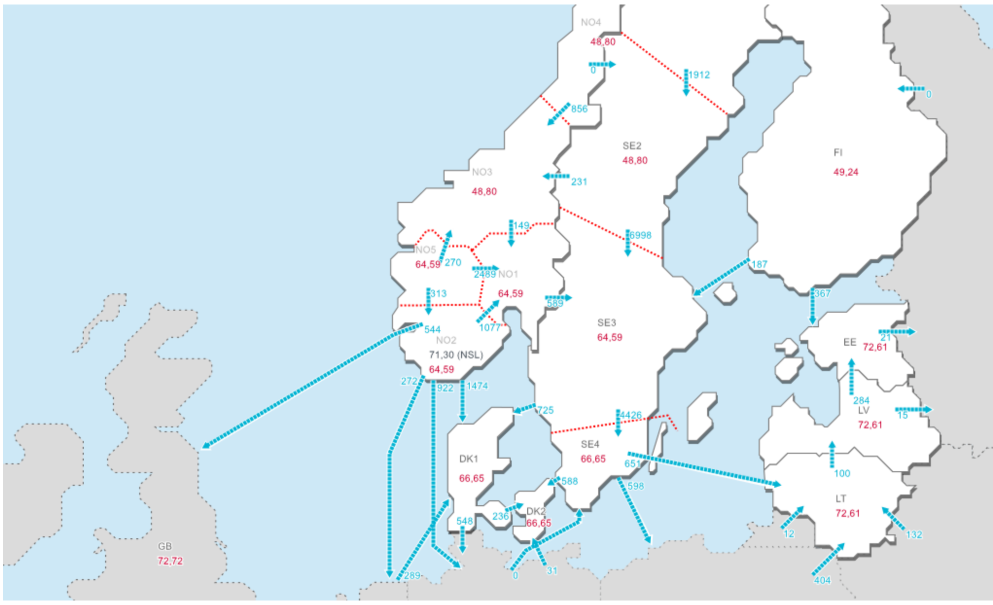


Figure 10 Example of power flow between Norway and other countries. Source: Statnett

These cables are connected to the same price zone in Norway (NO2), where Stavanger airport is located. Opening these cables has significantly increased difference between the five existing price zones in Norway and the overall price volatility, especially in NO2. During the recent energy crisis in summer 2022, the exceptionally high electricity prices propagated to Norway. This raised once again the question of how to mitigate the question of price uncertainty in the future.

5.2.3 Energy system scenarios

Designing of the future scenario for the Stavanger airport is intended to meet several strategic and operational goals, which are thoroughly reflected in the Avinor's overarching corporate policy (see [34]). More specifically it can be emphasised the Norwegian aviation sector's goal of being fossil-free by 2050 and working according to circular economy principles.

For Stavanger airport the corporate goals can be more specifically realised via anticipated test-implementation of electric airplanes. The aircrafts will probably be tested on a short route between Stavanger and Bergen with 30 min flight time as it is shown in Figure 11

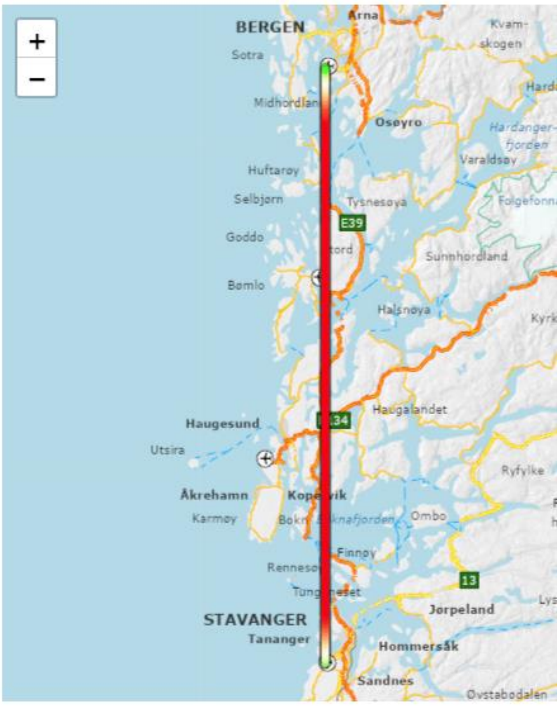


Figure 11 Planned connection between Stavanger (SVG) and Bergen (BGO) for electric aircrafts.

Energy consumption for electric aircraft was modelled based on:

- Coordinates for start- and endpoint
- Weight, drag coefficient, drag area, wingspan, wing area, thrust force, propeller efficiency, accessory load
- Preferred speed, acceleration and deceleration

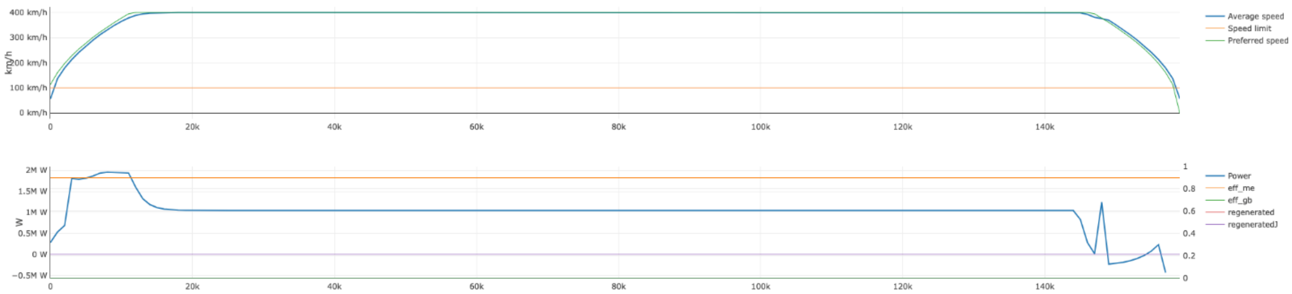


Figure 12 Estimation of energy demand per flight.

The data were further linked to specific battery types and applicable chargers. With overall expected energy consumption of 200 kWh pr trip/plane, two planes are estimated to have a demand of 12 MWh pr. week. The figure of 200 kWh was indicated by the vendor and later cross-checked with data for 9Bolt airecraft [39] and appears to be close. Based on planning of realistic time schedules for two (2025 and 2027) and four (from 2030) operational electric airplanes, this means increasing of electric capacity with 0.6 MW and 0.9 MW accordingly.

Scenario for 2025

It is expected that electric airplane fleet will operate in the airport in 2025 with two electric aircrafts. The planned destination is Bergen. The flying time is around 30 minutes and the turnaround time from landing, taxing, charging, boarding and take-off is 60 minutes. The overall energy demand for one way travel from Stavanger to Bergen, including various losses is 216 kWh. The initial plan for charging infrastructure is with 600 kW chargers. The schedule is assumed to be every 2 hours starting from 6 am in the morning and until the last operational flight leaving Stavanger at 8 pm in evening and the last landing is at 9 pm. If the first aircraft takes off at 6 am from Stavanger, it will reach Bergen at 7 am. After one hour of turnaround time, it takes off from Bergen at 8 am and reaches Stavanger at 9 am and charges for the next fly. Similarly, the second aircraft that leaves at 10 am from Stavanger will come back to Stavanger at 1 pm. The total round trip for an aircraft is 3 hours. Both aircrafts will be anchored at Stavanger at night and adopt slow charging. Figure 13 shows the charging scenario for year 2025 with 2 electric aircrafts and 600 kW chargers.

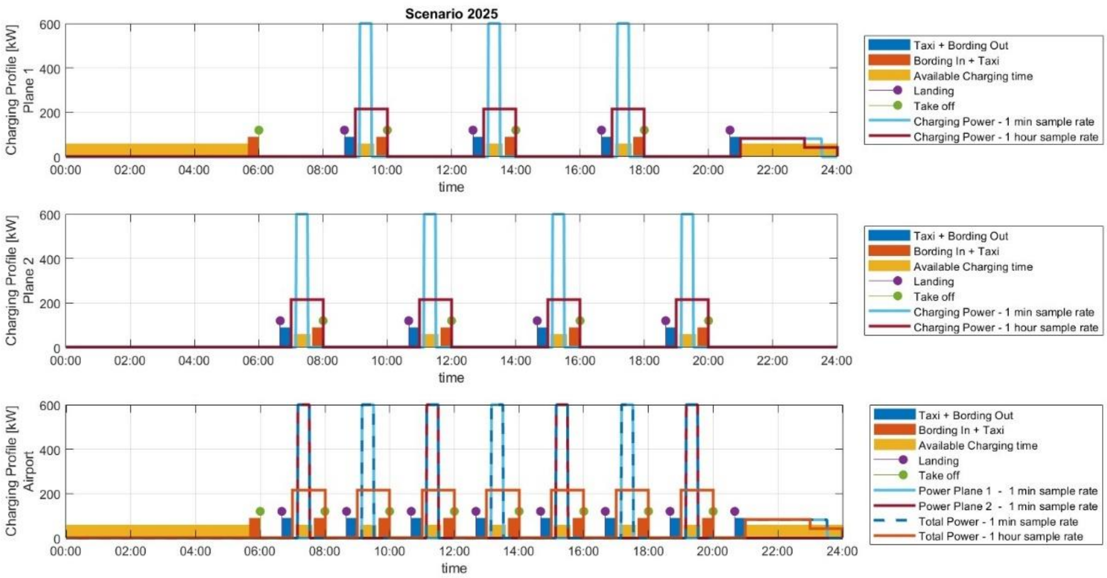


Figure 13 Charging scenario in 2025 (two aircrafts)

Scenario for 2027

In 2027, there will be four electric aircrafts and the service will be scheduled every hour. 2 of the aircrafts will be anchored at Stavanger and 2 will be anchored at Bergen at nights. **Error! Reference source not found.** shows the charging scenario for year 2027 with 4 electric aircrafts and 600 kW chargers. Plane 1 and 2 starts from Stavanger in the morning whereas Plane 1 and 4 will be anchored back at Stavanger at the end of day.

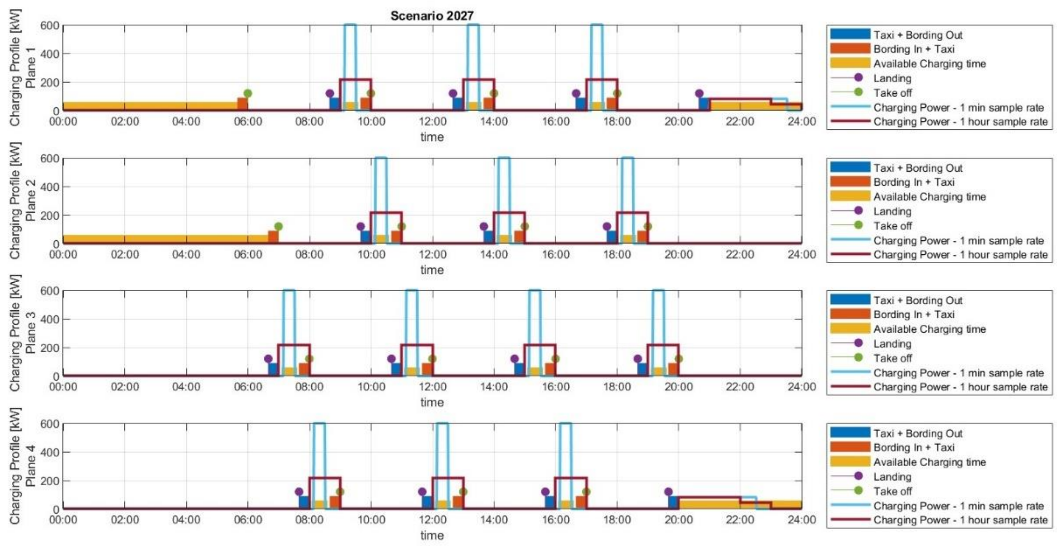


Figure 14 Charging scenario in 2027 (four aircrafts)

Scenario for 2030

In 2030, there will be 4 electric aircrafts and the service will be scheduled every hour. 2 of the aircrafts will be anchored at Stavanger and 2 will be anchored at Bergen at nights. Here the chargers are upgraded to 900 kW, which reduces the charging time to 10 minutes from 15 minutes. The frequency of flights can be increased from every one hour to every 45 minutes to maximize number of possible flights per day. Figure 15shows the charging scenario for year 2030 with 4 electric aircrafts and 900 kW chargers.

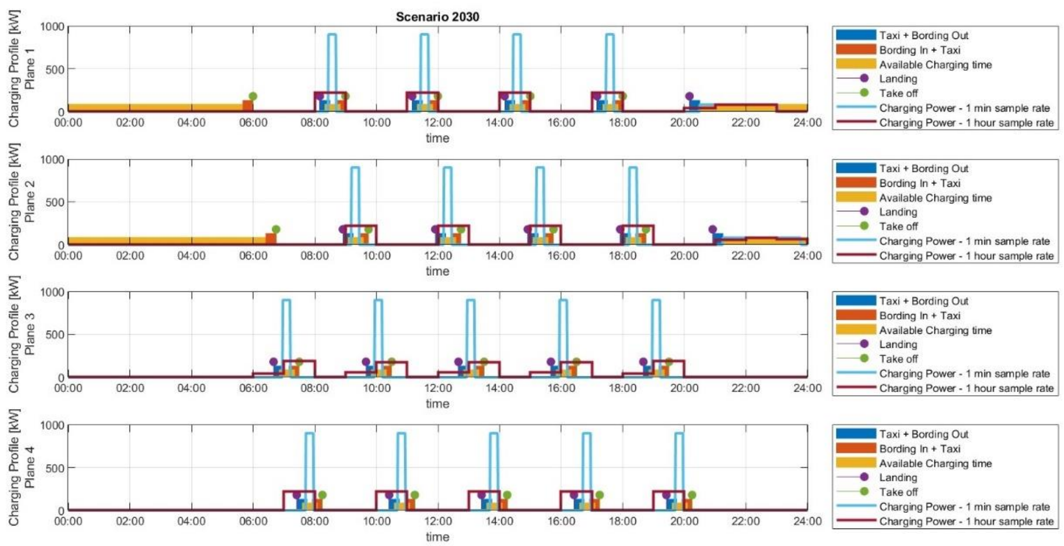


Figure 15 Charging scenario in 2030 (four aircrafts).

The growth of the demand is expected to continue in 2030-2040 and according to outcomes of Elnett21 project is expected to reach the base load of 5 MW and max load level of app. 15 MW after 2030, which exceeds capacity of the existing supply with 10 MW.

5.2.4 Technological and non-technological solution pathways

Deployment of electric aircrafts and corresponding increase of the electricity demand will require a substantial update of the existing grid components with several solutions applicable, including upgrading capacity of the existing substation from 5 MW to 15 MW by adding or replacing the transformer or even increasing the voltage from 15 kV to 22 kV. According to the Norwegian legislation the local DSO will require substantial compensation from the airport [40]. Therefore, the airport searches for possibility to increase the local electricity generation and replace a part of it, which is used for heating purposes (heating airplanes with hot air) with other sources. The following investment options have been assessed. The new layout of the energy system is presented in where optional investments are shown with stippled lines in Figure 16.

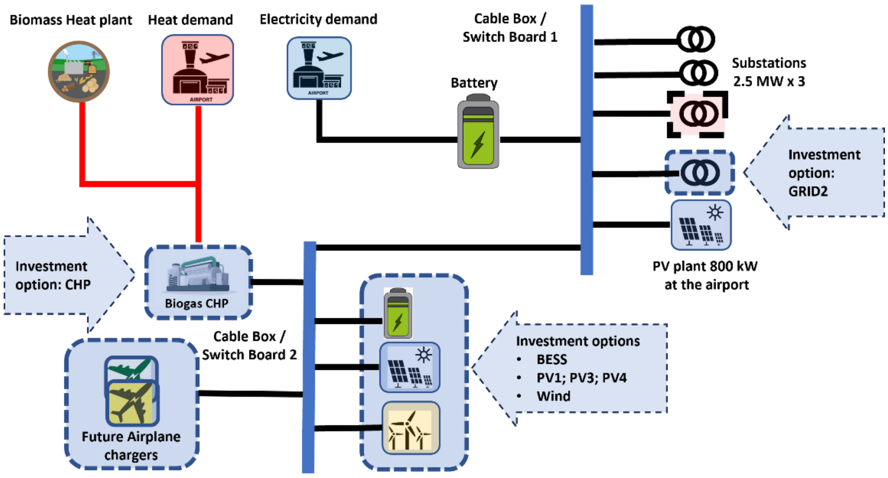


Figure 16 The assessed investment options (simplified).

- Photovoltaic: ***PV1; PV3; PV4*** - three separate installations with 2 MW max generation capacity each.
- Wind power: ***Wind*** - 4x250 kW windmills as single installation.
- Combined Heat and Power: ***CHP*** - 500 kW gas (biomethane) engine, with heat as operational model priority.
- Additional battery covering daily deficits for charging airplanes: ***BESS*** - 300 kWh.
- Extension of the existing grid capacity: ***GRID2*** - capacity increase with 10 MW

The new layout involves coupling of different energy carriers is presented in Figure 17

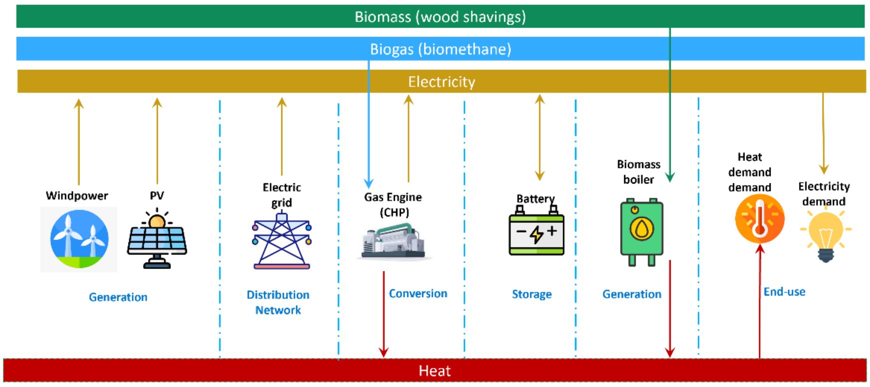


Figure 17 Energy carriers in Stavanger airport.

5.3 Modelling framework implementation

Shaping the modelling framework utilises functionality of Integrate tool, which can combine different non-mutually excluding investment options in different time steps in order to find an optimal solution.

5.3.1 Modelling framework description

The optimal investment plan is defined as the combination that minimises the discounted net present value of all costs in the planning period, i.e. operating costs plus investment costs minus the rest value of investments. The optimal plan will therefore identify the optimal design of the energy system (i.e. the optimal state) in different periods.

The main data inputs into the model are defined as:

- Stochastic data, which include two representative periods (winter and summer) each 168 hours long (seven days with one hour resolution) for each of the three analysed periods. This type of input is used for most of the components, both in terms of supply, demand, generation etc. This means in practice that for example for windmills input will include six different generation profiles with 168 hours each.
- Investment and operational costs parameters are defined separately for each investment alternative and include capital costs, lifetime, and operational costs.
- Other technical inputs include more specific technology related data, as for example efficiency ratios and heat/electricity operational priority for CHP.

Development of the electricity demand (input data)

The Integrate model uses representative periods i.e. two weeks (2x168 hours) pr. year. Therefore, within the given period the load development was estimated in fairly conservative way, based on the existing load profiles with gradual increase of the demand due to stepwise electrification of the operation and introduction of electric aircrafts. The estimated figures for the base load development comply with the outcomes of the Elnett21 project. The estimation shows a significant increase of the present base load as it presented in Figure 18.

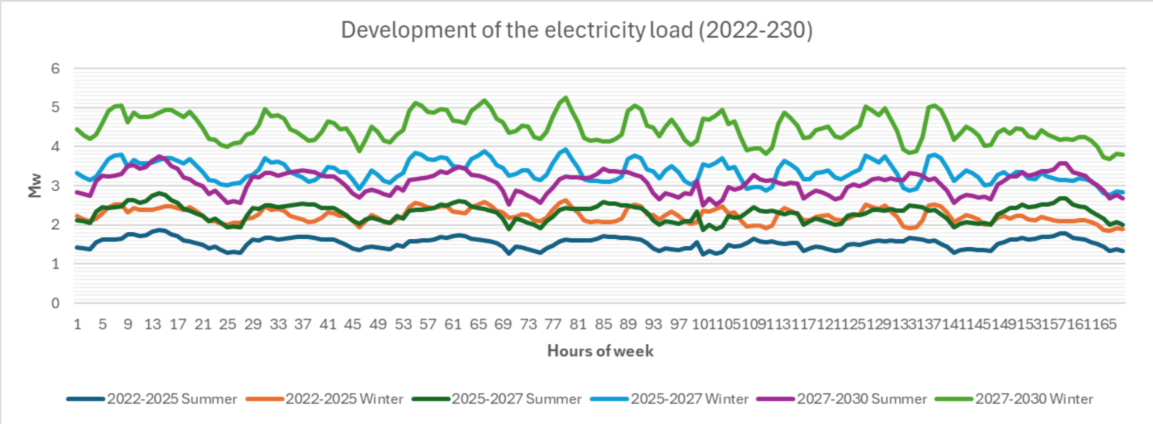


Figure 18 Input data for development of the electricity load (representative periods).

Costs for electricity supply from the conventional grid combine the electricity prices (spot price) and network tariffs for the high voltage connection, so-called level C (10-22 kV) from Lnett[9], the local DSO. The network tariff includes a separate capacity charge NOK/kW and energy charge NOK/kWh. For the sake of simplicity, the study did not consider the reactive capacity charge.

Extension of the existing grid capacity

Upgrading the existing substation is also one of the investment options (GRID2). Since there is no detailed knowledge of the final configuration for expansion of the grid, the construction charge costs were estimated as 10 MW of additional capacity and linked to the previous estimations done at SINTEF [41] and adjusted for the price increase. According to the existing practice, if it is necessary to build extra network capacity, the construction charge costs can be distributed proportionally between the main consumers [40]. Lifetime for the transformers are 45 years and suggested discount rate is 4%.

One of the main challenges is to collect correct cost data for the different components included into the investment options.

Installation of additional PVs

Possible generation profiles PV investment options are based on data generated by free online tool[10] for Stavanger area. Comparing data from this tool with historic load profiles showed that predictions were very close. Representative data (one week/168 hours) were selected for summer and winter periods (see Figure 19). It is also interesting to mention that the airports's electricity consumption during the summer period remains to be quite high due to high demand for cooling. This matches quite well with higher electricity outputs from the PV panels.

9 https://www.l-nett.no/nettleie/priser-og-vilkar-bedrift/
10 https://www.renewables.ninja/

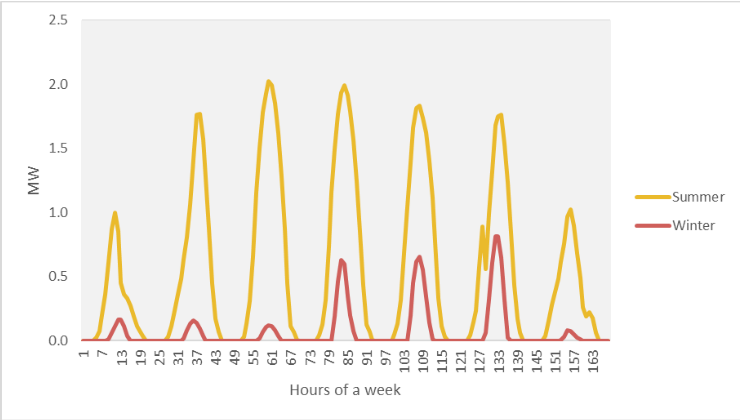


Figure 19 Expected generation profiles (winter and summer) for 2 MW solar park for Stavanger area.

Investment costs were approximated, based on the open data. According to Avinor, the already installed solar panels so far have not required significant maintenance and were able to sustain very heavy winds. Based on the present operational experience, it was assumed that the PVs will require very limited maintenance during their lifetime. Therefore the operational costs for the PV panels were not included into the modelling.

Installation of CHP (biomethane)

In general CHP is intended as heat sources for warming-up airplane hulls during cold periods. Today electricity is used for this purpose and the process appears to be very energy-intensive.

Biomethane has been selected as a prioritised fuel due to its climate neutrality and as well as its availability in the area nearby Stavanger airport. Rogaland county is one of the main agricultural areas in Norway with a long history of biomethane production and infrastructure available. One of the main advantages of biomethane is its technologic maturity and possibility to use biomethane as seasonal storage.

Input data for the model were collected via a dedicated meeting between Avinor, Klepp Municipality (producer of biomethane) and SINTEF in April 2023. In addition to this, Avinor had previously a technical study for alternative energy supplies at Svalbard, where biomethane was one of the options. Based on results of this study, gas engines (500 kW in total) were selected as CHP technology and figures related to the investment costs were defined.

Installation of Wind Power

Already in 2017 Stavanger airport had a dedicated technical study of the feasibility and viability of the installation of wind turbines in the vicinity of the airport, including:

- Potential of wind production
- Wake effect and interaction with air traffic
- Shadow flickering
- Construction methodology and cost

In brief, the study concluded that the most suitable installation would be deployment of several 250 kW turbines with max height of 30 meters. Based on historical wind speed data the average capacity utilization level for a 250 kW turbine would be about 21%. Limitation of the height and selection of an appropriate location allows to operate the turbines without creating disturbances to operation of the airport. Based on this feedback, the study considered building of four wind turbines with total generation capacity of app. 1 MW.

The Integrate tool requires hourly data for running the optimisation. The study therefore used Nordex N29 250 as reference turbine both in terms of generation profile and investments. For 30 meters hub height in Stavanger location the annual production for one turbine in Stavanger airport based on generated profile for 2019 will be around 0.625 GWh pr. year with max 234 kWh pr hour and average utilisation factor of 21.5% as it is presented in **Error! Reference source not found.**, which is very close to results of the above mentioned previous study.

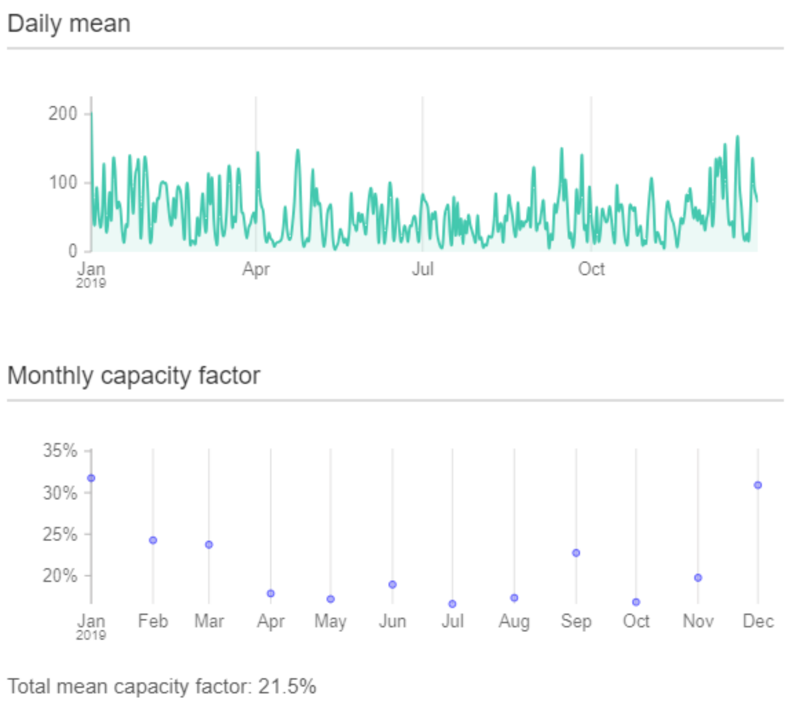


Figure 20 Expected generation profiles for one 250 kW wind turbine (Nordex N29 250) in Stavanger area. Source: https://www.renewables.ninja/

5.3.2 Airport energy system model implementation

The energy system was implemented in Integrate, resembling the main elements of the existing topology and the alternative investment options. Figure 21 shows the final implementation of the model, where solid lines indicate the existing infrastructure and stippled lines indicate the investment alternatives.

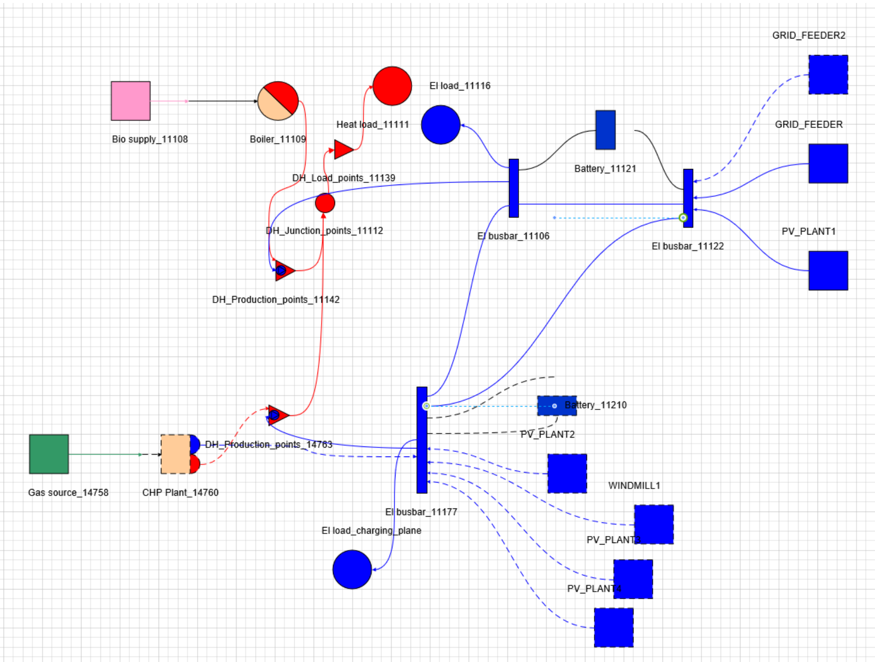


Figure 21 The final implementation of the Stavanger airport in Integrate tool.

The model includes three time periods: 2022-2025/2025-2027/2027-2030 with gradual increase of the electricity demand as it was described in the previous sections.

The initial idea was to create four alternative sets of scenarios with pre-define selection of technical solutions in each of them and compare these scenarios, based on the pre-determined increase of the load towards 2030. However, functionality of the Integrate tool allows to combine different investment options in a more flexible manner and thus to find the optimal investment solutions. Therefore, it was decided to define multiple investment options, which are technically applicable in the given geographic area and can be deployed at the airport without creation of any issues regarding technical safety requirements. As it was mentioned in the previous section, deployment of wind power is somehow limited with max height permitted nearby operational runways.

5.3.3 Handling of model uncertainties

The major uncertainties in the model are related to the input data:

- **Costs related to the new components:** The assessed scenarios include adding of several new components to the system e.g. combined heat and power (CHP), windmills, PVs, battery energy storage (BESS) and extension of the corresponding networks with the necessary civil engineering scope. Without a proper estimation relying on quotations from vendors, the level of the expected capital investments is very uncertain and cannot be used for decision-making without further refinement of the input data. Therefore, the present study creates a methodology for comparative assessment of alternative expansion scenarios, rather than an accurate and final investment decision. Prices for the components were estimated, based on the recent examples whenever it was possible, while operation and maintenance costs are based on either percentage from the capital investment e.g. prices for electric transformers or proportionally to the electricity output e.g. windmills.

- **Prices for the energy carriers:** The recent energy crisis in Europe reminded us how challenging it can be to predict prices for conventional energy carriers. As it was mentioned previously, Stavanger airport is in NO2 electricity spot price area, which is very exposed to price fluctuations. This price zone also appears to have higher electricity prices, than the rest of the country due to power cables to the continent. This is probably one of the most sensitive inputs to the model, so several simulations were done with different price inputs, as for example flat prices vs. gradual increase. In general, this does not seem to change the outcomes – selection of the investment options significantly.
- **Mature technologies:** In order to mitigate any potential issues related to missing technical or legal frameworks, the study initially prioritised mature and well-established technologies as for example selecting gas engines (biomethane) for CHP.
- **Configuration of the distribution network tariffs:** This represents an additional uncertainty in the scope of the study. The present structure and prices from the local DSO (Lnett) are included into the optimisation. Avoiding additional investments into grid expansion by increasing of locally produced energy also means considerable cost savings for the distribution network tariffs, since the imported electricity volumes and max capacity will be significantly reduced. However, the present tariff structure can be changed in the future since production "behind the meter" still requires ancillary services from the main grid as for example frequency support. Still such a change is unlikely to happen in the close future.

5.4 Robust smart energy hub concept(s)

The model evaluates seven different investment options over three time periods or 448 operational analyses to select the ten best combinations of the investment options (see Figure 22). The simulation time is about 50 minutes.

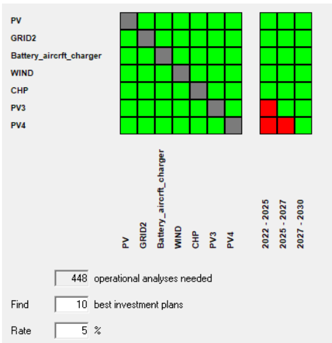


Figure 22 Initiation of the optimisation process.

5.4.1 Presentation of modelling results

The simulation results present a combination of capital and operational expenditures for each period, while the final ranking is based on the estimated annuity costs for each alternative as it is shown in Figure 23.

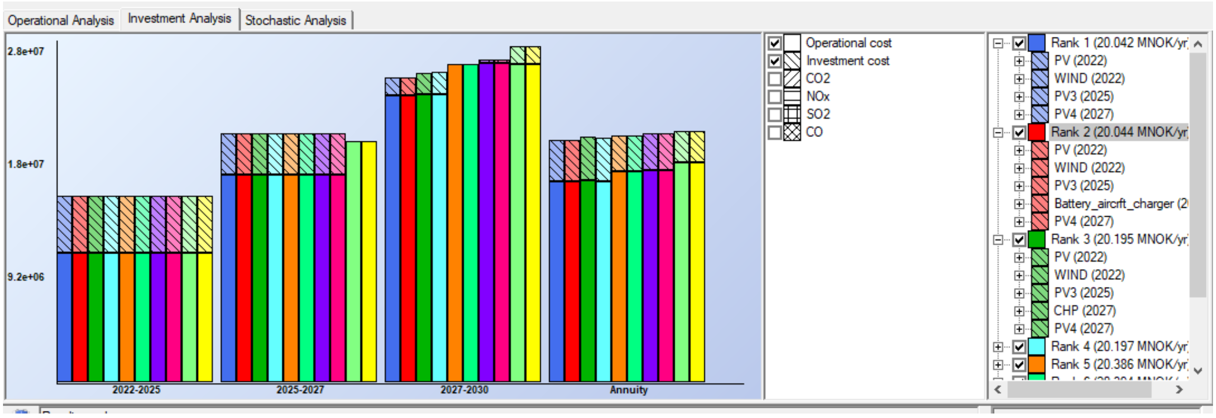


Figure 23 Presentation of the modelling results in Integrate tool.

The selected investment options have relatively small differences between them since they were selected from several hundreds of the operational analyses, which were done. The same results are presented in tabular form in Table 1.

Table 1 Presentation of the modelling results in tabular form (annuities only). Explanation of the investment options in the last row.

Name	2022-2025	2025-2027	2027-2030	Total_annuity [NOK]
Rank 1	PV1, WIND	PV3	PV4	20 042 315
Rank 2	PV1, WIND	PV3	Battery_aircraft_charger, PV4	20 044 354
Rank 3	PV1, WIND	PV3	CHP, PV4	20 195 080
Rank 4	PV1, WIND	PV3	Battery_aircarft_charger, CHP, PV4	20 197 119
Rank 5	PV1, WIND	PV3		20 386 268
Rank 6	PV1, WIND	PV3	Battery_aircarft_charger	20 393 959
Rank 7	PV1, WIND	PV3	CHP	20 539 033
Rank 8	PV1, WIND	PV3	Battery_aircarft_charger, CHP	20 546 724
Rank 9	PV1, WIND		PV4	20 683 883
Rank 10	PV1, WIND		Battery_aircarft_charger, PV4	20 691 574

- Photovoltaic: ***PV1; PV3; PV4*** - three separate installations with 2 MW max generation capacity each.
- Wind power: ***Wind*** - 4x250 kW windmills as single installation.
- Combined Heat and Power: ***CHP*** - 500 kW gas (biomethane) engine, with heat as operational model priority.
- Battery aircraft charger: Additional battery covering daily deficits for charging airplanes - 300 kWh.
- Extension of the existing grid capacity: ***GRID2*** - capacity increase with 10 MW

The model uses several KPIs for ranking the results: combination of capital and operational costs and estimation of the annuities, which is the primary indicator, used for selection of the most feasible solutions as it is presented in Table 1. The model also allows us to use emissions as KPIs, but this is not directly applicable in this case, since all the initial investment alternatives are emission-free.

When it comes to uncertainties, related to energy prices, the complexity of the input data does not allow exploring of possible outcomes related to changes of the input data. However, it appears that there is a certain balance between price for electricity imported from the conventional grid and prices for biomethane. If electricity prices stay on the present level, utilisation of the CHP remains to be limited. However, increase of electricity prices in the conventional grid (especially on seasonal basis) leads to higher utilisation of CHP due to more stable prices for biomethane.

Initially the investment option related to deployment of an additional electric battery was added mostly for operational purposes. This was based on the previous experience related to use of electric ferries in Norway. High capacity and short time charging created voltage violations in the local distribution network and required installation of additional buffer batteries onshore for voltage support. Following this experience, a 300-kW battery was added with max discharge rate of 300 kW. The simulation results show that in several investment configurations (Rank 2, 4, 6, 8 and 10) it appears that the optimisation model utilises batteries as a buffer between the loads and the intermittent part of the generation i.e. PV and Wind to minimise imports from the grid. It is illustrated in Figure 24.

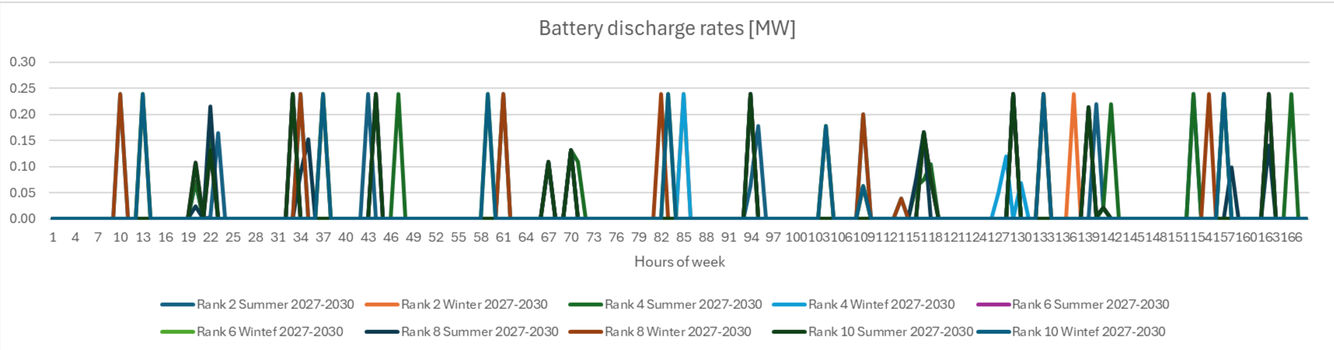


Figure 24 Battery discharge rates in different investment options.

Therefore, it was done an attempt to assess what size of the battery would be necessary to act as a complete buffer securing electricity supply despite daily fluctuations from PV and wind power assets. The assessment indicates that the buffer's capacity should be quite high (up to 4 MW) and accordingly very costly (see Figure 25).

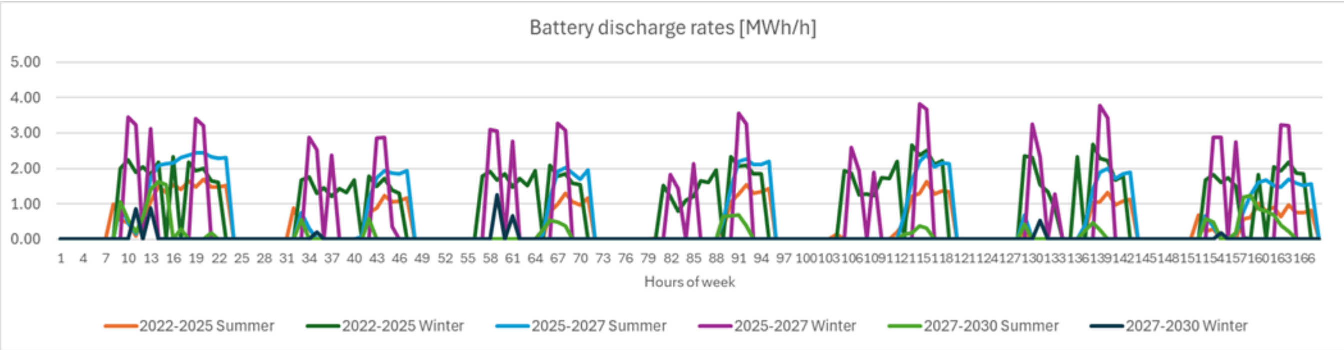


Figure 25 Evaluation of battery sizing.

5.4.2 Evaluation of modelling results

The modelling results indicate a clear priority towards deployment of the local renewable generation as it is shown in Table 1. This happens despite high level of the investment costs, which are required for the deployment. It seems that fairly low operational costs and long lifetime for the renewable assets, especially the PV justify the initial investment.

The study indicates that robust and environmentally friendly transition can be achieved by efficient utilisation of the locally existing resources. Since the local conditions may vary from area to area, the winning solutions will vary accordingly in order to meet the domestic needs e.g. heating vs. cooling and to achieve the best utilisation of the available resource base.

This also requires a significant level of diversification between these resources and introduction of energy coupling, so the airport will not become critically dependent from one supplier, which may exercise its market power. Cogeneration systems can further decrease reliance on electricity grid, but local supplies of green fuels must be secured in terms of availability and pricing. Considering operational reliability, it will be reasonable to explore the Rank 4 combination components as viable configuration for the energy system.

Deployment of integrated energy systems with high level of renewables increases the complexity, both in terms of initial planning, expansion, and operation. This requires dedicated tools for optimisation of the daily operations. The existing energy management systems (EMS) are most suitable for operation of office buildings, while an airport is a far more complicated system with higher priorities for fault-free operation.

In addition, introduction of new energy carriers in real-life often requires creation of new business models, which should be duly modelled and assessed. This is not in the scope of the present paper and can be suggested as a next step activity.

5.4.3 Robust smart energy hub concept(s)

Selection of mature technologies reduces risks: Stavanger airport focuses on solving very specific and rather short-term challenges, i.e. rapid increase of the load, and selects more mature decarbonising technologies as PV, windpower and biomethane.

Energy self-sufficiency: The recent experience with extreme volatility of prices for electricity during the second part of 2022 makes the airport to recognise the necessity to increase self-sufficiency and introduce energy coupling for more flexible operation and resilient operation. This can be achieved by utilisation of local resources, improving sustainability and robustness of the energy system, mitigating several risks and uncertainties, e.g., price volatility for centrally dispatched electricity. In case of Stavanger airport biomass and biomethane are two climate-neutral fuels, which are locally available. Compared to electricity, these fuels turn to have more stable (often seasonal) prices and can be easily stored. Availability of biomethane enables quick, environmentally friendly deployment of CHP. In addition to this, the available area becomes an important resource, which can be utilised for deployment of solar and wind generation.

Diversification of the energy supplies: Historically electricity prices in Norway were fairly low due to massive development of hydropower generation. After gradual introduction of the power connection links to the neighbouring countries during the recent years the electricity prices in Norway, and especially in NO2 price zone have become influenced by the electricity prices on the continent. The growing level and volatility of the electricity prices makes industrial consumers to look for solutions, and diversification of energy supply can be a relevant strategy. Outcomes of this study assess introduction of the new energy sources and thus achieve a higher-level diversification.

Reduction of CO2 emissions from the aviation: As it was mentioned above, the Norwegian power system is dominated by environmentally friendly hydropower. This makes it even more necessary to reduce CO2 emissions from other sectors. In our case the foreseen introduction of the electric aircrafts allows reduction of CO2 emission from air traffic. The increase of the electricity consumption can be covered by the local sources. Introduction of electric aircrafts serving 18 trips pr. day between Stavanger and Bergen replaces 162 passenger-trips between Stavanger and Bergen every day. Considering that according to ICAO's official methodology [42] this leg generated 33.8 kg of CO2 pr passenger, the total abatement of 5 476 kg CO2 can be achieved every day.

5.5 Conclusion

The study shows that a considerable part of the growing energy demand at the airport can be compensated by efficient utilisation of the available local resources. In particular this applies to utilisation of the available area at the airport for installation of PVs and wind power. The area is not used for any other purpose, so deployment of the local renewable generation does not create additional significant disadvantages for the society or for the surrounding environment. This situation is probably similar to many other airports, and this experience can be as well replicated.

Other local resources available in the county of Rogaland are biomass and biomethane. Utilisation of these resources allows more flexible operation of the airport due to more stable prices (often seasonal) and possibility to store the energy carrier. Furthermore, availability of biomethane enables quick, environmentally friendly deployment of CHP introducing energy coupling to the system.

In more practical terms, another significant advantage is that the study relies entirely on the technologic solutions, which can be considered mature. This means that they can be deployed fast, with minimum surprises and operational risks later on.

Deployment of integrated energy systems with high level of renewables increases the complexity, both in terms of initial planning, expansion, and operation. This however allows to use energy coupling for more flexible and resilient operation. Finally, electrification of end-uses will trigger a significant rise of electricity demand. When electric planes are included in the equation, the rise in power demand and grid load assumes dramatic dimensions. However, transport hubs can find effective solutions in well-developed local production, storage and exchange of energy to cope with increased demand and avoid expensive grid expansion projects.

6 Larnaca Airport – scenario study and system design concepts

6.1. Introduction to the airport

6.1.1.1 General introduction of Larnaka airport

Figure 1: Larnaka Airport Aerial Photo

Larnaka International Airport is Hermes Airports Ltd and is the main gateway to Cyprus, serving over 8 million passengers in 2023.

It is a single runway (04/22) airport featuring 28 aircraft parking stands for commercial aviation/movements, 8 bus/remote gates, and 16 passenger boarding bridges and operates round-the-clock, year-round.

The airport is structured across five floors. The basement houses general operational facilities, maintenance and offices, while the ground floor hosts bus/remote gates, maintenance offices, Hold Baggage Screening Room, arrival baggage reclaim, meet and greet areas, as well as shops, restaurants, and other offices. Level one serves as the arrivals area and facilities various offices. The departures section occupies the second floor, featuring shops, restaurants, offices, check-in counters, security areas, and gates. Offices and some mechanical rooms are situated on the third level.

Externally, the airport offers over 2,500 parking spaces, along with offices, electric vehicle charging stations, cafes, and supplementary buildings and services. These include the air traffic control tower, fire brigade building, cargo sheds, maintenance facilities, aircraft hangars, and maintenance stations.

More details on the airport are provided in the Annex to this Report and is available on Hermes website www.hermesairports.com.

6.1.1.2 Hermes Climate and Energy Strategy

Hermes Airports is committed to leading initiatives aimed at mitigating global warming in accordance with the Paris Agreement. This involves enhancing energy efficiency, managing and reducing greenhouse gas emissions, and optimizing the utilization of natural resources. This commitment aligns with the goal of achieving net zero emissions by 2050, maximizing efforts toward decarbonization.

6.1.1.3 Airport's Environmental Policies

Hermes Airports Ltd adheres to a defined Environmental Policy, which sets clear objectives for emissions and pollution management. The primary goal is to manage energy usage and greenhouse gas emissions actively, thereby reducing the environmental footprint of operations. Therefore, it is imperative for Hermes to:

- Optimize energy usage in a manner that is efficient, cost-effective, and environmentally sustainable.
- Minimize the environmental footprint of airport operations and activities.
- Explore and implement green energy solutions that benefit airports, stakeholders, and communities while enhancing community awareness and involvement.
- Ensure compliance with all relevant laws and regulations.
- Promote and work towards greener and eco-friendly airports and the environmental protection as part of Hermes' ESG (Environmental, Social, and Governance) responsibility.
- Implement strategies and measures to conserve energy, reduce carbon emissions, and mitigate the environmental impact of airport operations.
- Maximise the utilisation of the renewable energies in Hermes' energy mix

6.1.1.4 Energy Types

Due to the limited scale and Cyprus's energy grid from mainland Europe, there exists a high carbon intensity, with only a small portion of renewables being utilized. According to the latest data from the Transmission System Operator of Cyprus, renewable energies such as wind and solar power account for only 15.6% of Cyprus's total energy production, while the remaining 84.4% is generated through the burning of fossil fuels.

This situation, combined with the absence of energy storage technologies on the island, results in a high carbon dioxide emission factor for each kilowatt-hour produced or consumed.

Photovoltaics

Hermes has developed a 3.5 MWp PV plant at Larnaka International Airport as part of its carbon reduction plan. The on-site photovoltaic plant contributes to approximately 28% of the airport's energy requirements and reduce the carbon emissions of the airport by more than 3,600 tons of carbon dioxide equivalent emissions per year. The existing plant occupies an area of 36,000m².

Figure 6.2, Larnaca Photovoltaic (solar) Park

6.1.2 Airport climate footprint and ambitions

Current Status and Footprint

Hermes made substantial investments in energy and carbon management, reflecting its fundamental environmental values and in April 2024 Larnaka Airport was accredited to Level 4+ " Transition".

Hermes' Carbon Footprint is attributed to a great part on energy consumption. Efforts and initiatives undertaken from 2010 to 2019 focused on reducing this component, which accounts for 96% of emissions directly managed by Hermes.

Airport's Ambitions, Objectives and Roadmap

In order to ensure sustainability is integrated into the business model and all parameters are addressed, Hermes has set up policies, strategy and strategic objectives using as reference the United Nations Sustainable Development Goals (UN SDGs), ACI Directives, and Cyprus National Action Plan.

These are transformed into a road map with Short, Medium and Long-Term objectives, targets and actions that would lead to the ultimate target of Net Zero. These are to be tracked and reviewed on an annual basis.

The main pylons of Hermes' Energy and Climate Strategy are focusing on the:

- Climate Change
- Energy Efficiency
- Clean Energy

Sustainable climate and energy management form part of the overall sustainability strategy of the Company.

Hermes has set these goals with the 2050 horizon however the intention is to monitor and replan so that their fulfilment could be achieved much earlier.

The roadmap of Hermes covers the majority of the planned actions and initiatives as presented in the existing strategy and translated into the following roadmap.

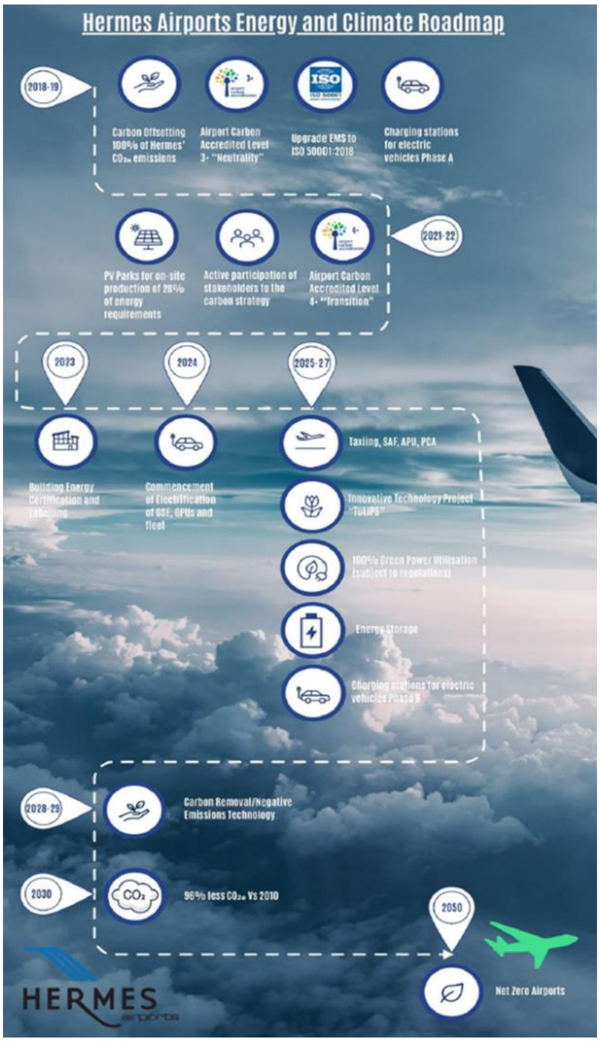


Figure 6.3, Hermes Energy and Climate Roadmap

<u>Hermes' Pathway to a Green Future</u>

Hermes' roadmap as developed in combination with the various initiatives identified led to the following green pathway as presented in the following graph.

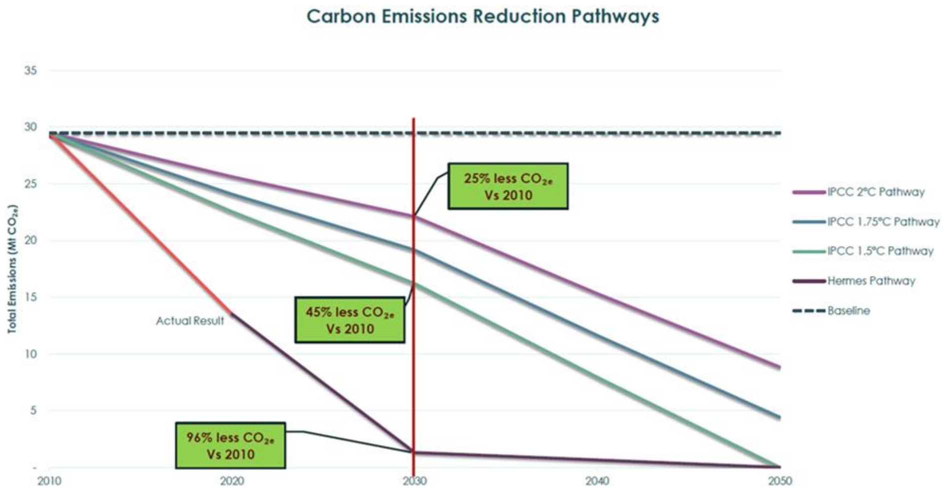


Figure 6.4, Carbon Emissions Reduction Pathways

According to the IPCC 1.5°C scenario, emissions are projected to decrease by 45% by 2030 compared to 2010 levels, while Hermes's plan is aiming to a 96% reduction in the same period.

Hermes' Carbon Footprint is attributed to a great part on energy consumption. The initiatives and actions in the period of 2010-19 were focused on the reduction of this element which corresponds to 96% of the emissions directly controlled by Hermes, as described above. The following graph provides a graphical representation of Hermes' directly controlled emissions.

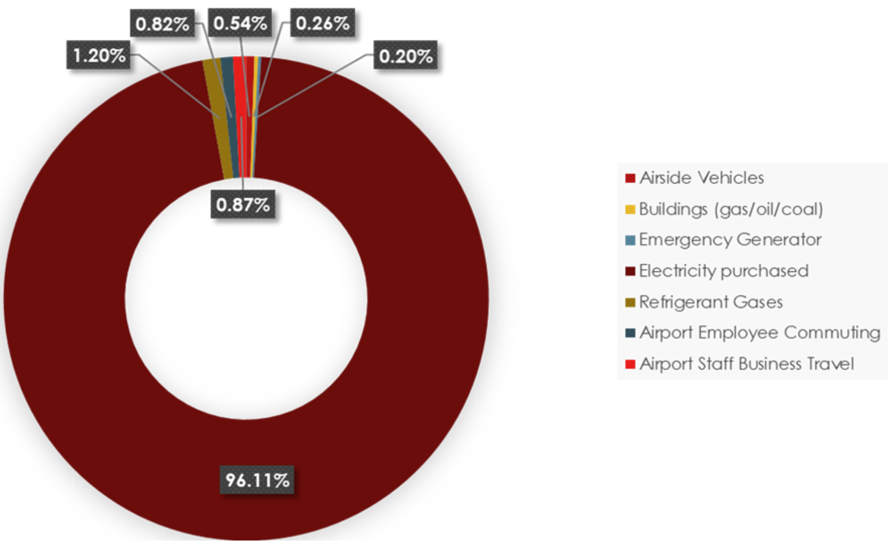


Figure 6.5, Hermes directly controlled CO2 emissions

By incorporating the indirect emissions (Scope 3) of the airport into the total airport's footprint, the percentage per emission source is significantly affected. Hermes controls only 8.5% of these emissions.

The main sources of the emissions are:

- Aircraft Landing, Taxiing, Take-off (36.9%)
- Public Access-Commuting (36.6%)
- Electricity Purchased (8.7%)
- Staff and visitors (8.5%)
- Aircrafts APUs (5.3%)
- Fleet (1.3%)
- Rest (2.6%)

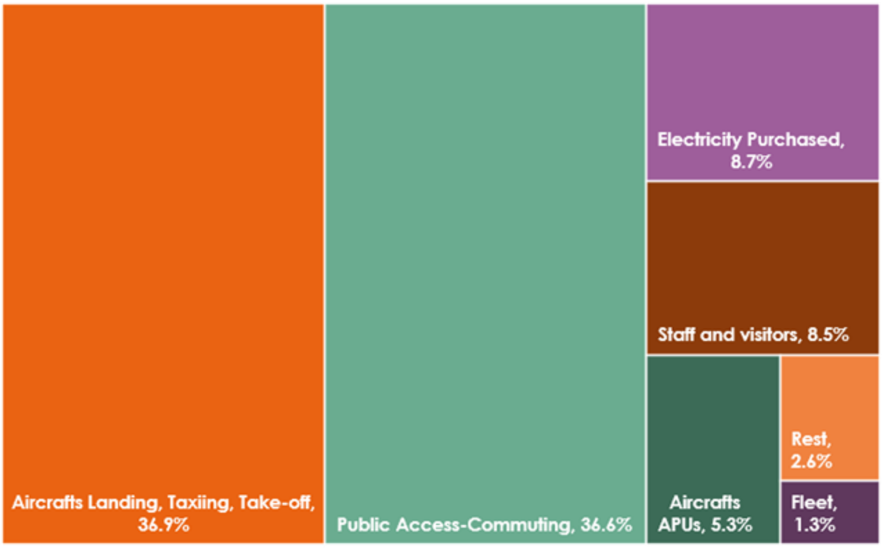


Figure 6.6, Sources of CO2 Emissions at Larnaka International Airport

The following table summarises the total Carbon Dioxide Equivalent Emissions of the Larnaka International Airport for the entire period such data is available.

Scope 1&2 Emissions	2014 (tCO_{2e})	2015 (tCO_{2e})	2016 (tCO_{2e})	2017 (tCO_{2e})	2018 (tCO_{2e})	2019 (tCO_{2e})	2020 (tCO_{2e})	2021 (tCO_{2e})	2022 (tCO_{2e})
Airside Vehicles	88.99	63.43	83.76	79.06	83.46	94.48	95.54	94.78	95.7
Airside Vehicles Kerosene	58.10	56.41	25.88	57.79	0.00	0.00	0.00	0.00	0.00
Buildings	72.70	80.70	76.40	68.90	40.09	65.86	40.36	42.35	56.5
Fire Training	37.50	52.40	55.00	30.44	0.00	30.88	0.00	29.41	0.00
Emergency Generator	9.50	32.90	23.30	22.76	30.52	9.18	9.00	28.99	37.3
Airport Scope 1	**266.8**	**285.5**	**264.3**	**259**	**154.1**	**200.4**	**144.9**	**195.5**	**189.5**
Airport Scope 2	**16,839**	**15,691**	**15,317**	**14,845**	**14,867**	**15,099**	**13,915**	**0**	**10,092**
Refrigerant-Scope 1	**583.6**	**532.4**	**516.3**	**530**	**186.2**	**97.5**	**0.00**	**239.2**	**134.7**
Airport Operator Total CO_2e emissions	**17,534**	**16,509**	**16.098**	**15,634**	**15,207**	**15,397**	**14,060**	**434.7**	**10,417**
Airport Scope 3	**n/a**	**n/a**	**n/a**	**n/a**	**174,695**	**171,841**	**169,084**	**101,116**	**506,931**

Table 6.1, Larnaca Airport Carbon Dioxide Equivalent Emissions 2014-2022

6.1.3 Airport business scenarios

The business plan of Hermes has been analyzed in the preparation of the simulation system for the future scenarios. This plan dictates several factors and parameters to be considered in the final system, such as:

- Five milestone years: the milestone years analyzed during the simulation includes the baseline year of 2019, the first intermediate milestone of 2027 (3 years after the finalization of the simulation), year 2030 (the last full year of Hermes' Concession Agreement for the operation of Larnaka International Airport), the 2040 year as an intermediate step towards the final/long-term target year of 2050. The final milestone is aligned with the net-zero target year of Hermes.
- Passenger traffic increase: Forecast of the passenger traffic shows an expected increase of approximately 2% per year. This was kept constant for the entire duration of the project and the scenarios for all milestone years.
- Meteorological conditions as per IPCC – RCP 2.6 as described above.
- Electrification of Hermes' own vehicles/fleet from 2024 onwards.
- Electrification of ground support equipment operating at the airport as per current Ground Handling rules. The rules dictate the replacement of 30% of the GSE every three years with electric equipment, aiming to fully decarbonization of the equipment until 2030.

- Photovoltaic plants capacity increase by 1.2MWp from the first milestone year, thus resulting to a system of 4.7MWp from 2027 onwards. Energy storage solutions also forms part of this scenario.

6.2 Methodology

6.2.1 Methodological framework used for the scenario analysis.

As carbon emissions are strongly linked to energy consumption in Cyprus, the following methodology focuses on reducing the power grid consumption of the airport to achieve carbon reduction goal. The methodology is based on the following steps:

Modelling the airport and its consumptions:

Collection and analysis of historic data (electricity, fuels, carbon emissions)

- Historic data on passenger traffic, staff, cargo and aircraft movements.
- Historical and IPCC Weather/Climate data for future scenario projection (from 2019 to 2050)
- Airport thermal dynamic simulation and modelling based on CAD geometry.
- Airport PV power plant simulation based on a PV irradiance modeling python script.

Calibration and first simulation model adjustments:

- Analysis of the first simulation results
- Adjusting the hypothesis based on the results and consumption data.
- PV model simulation for the year 2019

Scenarios simulation – Energy conservation measures and PV projection in future milestone years based on thermal simulation and IPCC scenarios.

- Natural ventilation potential for the airport building, quantification and results.
- Windows solar shading impact and quantification.
- Cooling temperature setpoint increase sensitivity and results relative to the building consumption.
- PV Projection in future scenarios based on IPCC weather projection and TDS of the airport building projected consumption.

6.2.2 Models and other tooling

IES VE 2023 modelling (Apache Thermal Calculator and Simulation tool)

The building energy consumption is calculated using dynamic thermal simulation. The dynamic approach to calculation accepts the building as a "living" object, reactive to external elements, and considers the response of materials to variations in internal (occupants, equipment, etc.) and external (sun, wind, etc.) thermal loads. In contrast, a static simulation considers the building as an inert object, a simple addition of materials. Static calculations, for instance, calculate theoretical solar gains, but are unable to determine at what level and how the building can make the most of them.

In a dynamic thermal simulation, thermo-aerodynamic phenomena are dealt with only at the macroscopic level, between rooms and/or between a room and its environment but have the advantage of being carried out in a dynamic regime, with variable boundary conditions. The air temperatures calculated are the average temperatures of the air volumes contained in the rooms, without considering vertical and horizontal gradients, unlike CFD studies. For the latter, thermal and aeraulic phenomena are treated microscopically, in steady-state conditions, enabling us to determine temperature, pressure, velocity, etc. at any point in the room.

In such a study, the building's thermal behavior is simulated throughout the year according to the building's local interactions with its environment, with meteorological data considered via a weather file.

Numerous other parameters, such as occupancy, temperature set points, ventilation rates, opening of windows and internal contributions from equipment (office equipment, lighting, etc.) are also considered in the calculation.

These parameters are detailed in the following paragraphs.

The multi-zone dynamic thermal software IES Virtual Environment version 2023 was used for this Energy Simulation. This tool is used to create a 3D building volumetry, define material properties, define internal inputs (equipment + occupants) and operating habits, to obtain refined building requirements.

The following modules were used in this study:

- ModelIT: Geometric modeling,
- Suncast: Dynamic shading calculation,
- ApacheSim: Dynamic thermal simulation,
- MacroFLo: Modeling air flows between indoor and outdoor spaces

- VistaPro: Detailed analysis of results by zone and for each component of the energy system.

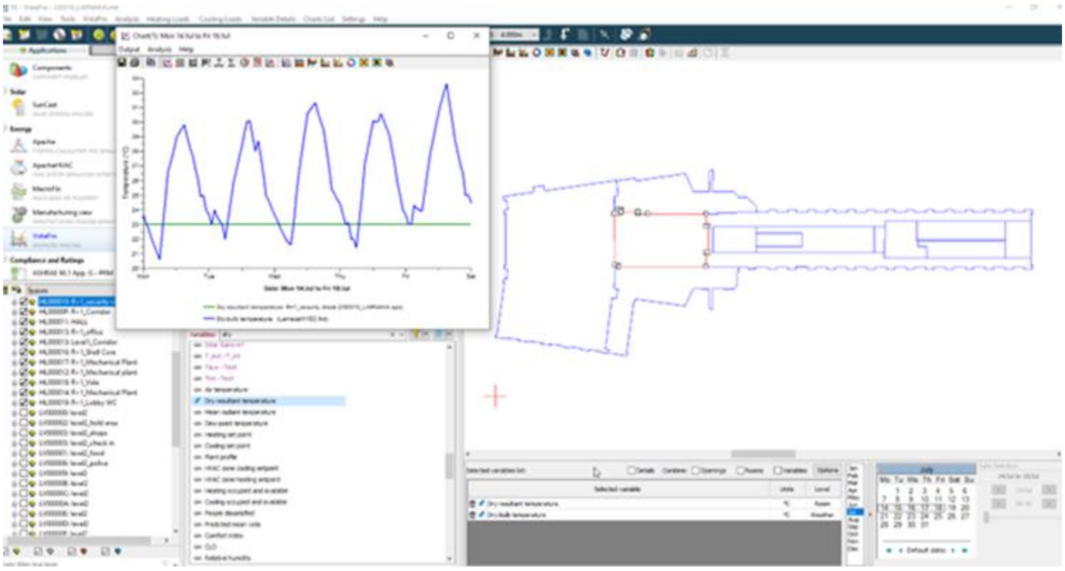


Figure 6.7, Exports from the dynamic thermal simulation model used.

IES is a dynamic thermal simulation software package with numerous applications in the field of High Environmental Quality. It can be used to analyze a building's behavior, component by component over time.

Modelling is, by its very nature, an attempt to translate real, variable and sometimes imperfectly understood situations into figures. A building's energy consumption is certainly impacted by its technical installations, but it is also highly dependent on usage, users and the weather. What's more, the thermodynamic laws of consumption efficiency are not always linear. As a result, thermal simulations and results are subject to theoretical limitations. Finally, since the models are based on fixed, homogeneous parameters, it is difficult to take account of the specific faults that can be found in a building. Sensitivity tests show that values should be read with a confidence interval of ± 15%.

<u>Python PV irradiance modeling script</u>

The PV study is based on the calculation of the incident irradiance on a given surface on the ground and on the calculation of the potential to exploit the incident and diffuse rays to produce electricity, directly exploited by the airport building. This method should enable a direct comparison to be made between the energy produced by photovoltaic panels and the hourly load curve obtained from the dynamic thermal simulation. In this way, the future scenarios derived from the TDS will be easily compared with the PV simulation, as shown by the following overview.

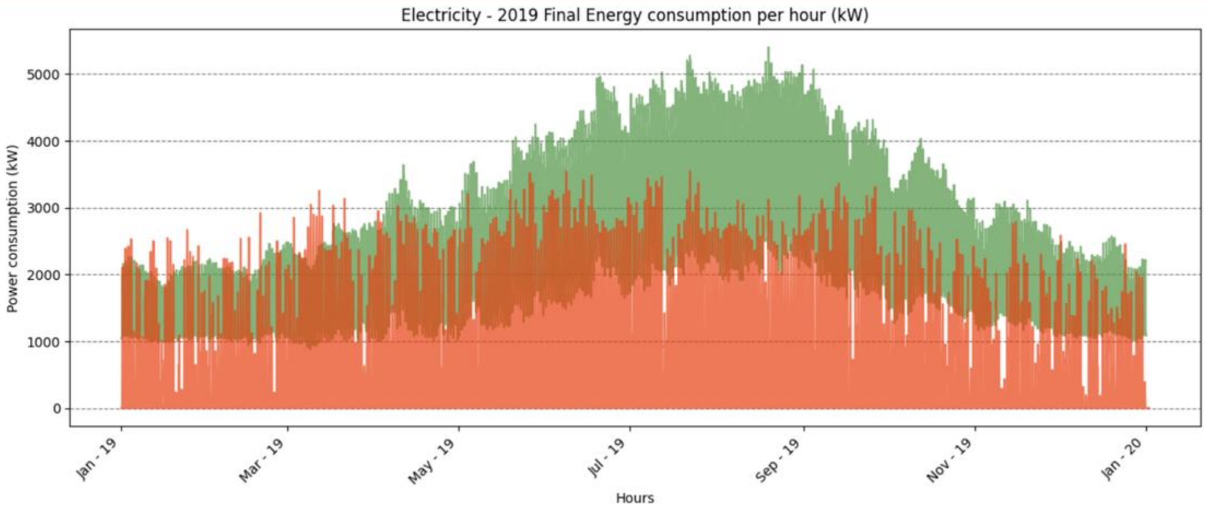


Figure 6.8, Comparison of the energy produced by the PV park and the hourly load obtained from the dynamic thermal simulation (On the x-axis, the time-one year, and on the y-axis the energy in kWh).

The chosen method corresponding to these criteria is a Python implementation of the methodology described in *Measurement and modeling of diffuse irradiance masking on tilted planes for solar engineering applications, Daniel Tschopp, Adam R. Jensen, Janne Dragsted, Philip Ohnewein, Simon Furbo, (https://doi.org/10.1016/j.solener.2021.10.083)* as this method allows the implementation of both direct and diffuse solar irradiance considerations.

This study examines the impact of obstructed views on diffuse irradiance distribution within fixed-tilt arrays, crucial for accurately designing and predicting power output in photovoltaic and solar thermal projects. It fills a research gap by analyzing how surrounding rows affect sky and ground visibility. High precision pyranometers were positioned in an experimental array with various row spacings and tilt angles.

A new model was developed to estimate diffuse tilted irradiance, considering obstructed views. Validation showed the model accurately represents diffuse irradiance distribution. Results reveal significant reductions in diffuse irradiance at lower collector sections, especially with narrow row spacings and steep tilt angles. For example, in the most extreme scenario, diffuse irradiance decreased by 64% at the bottom and 89% on average relative to the top, highlighting potential biases in performance assessments relying solely on top measurements. Utilizing the

"*Measurement and modeling of diffuse irradiance masking on tilted planes for solar engineering applications"* model is highly relevant for digital simulations of PV production in terms of:

- Irradiance prediction accuracy: The model accounts for obstructed views in fixed-tilt arrays, providing more precise estimates of diffuse irradiance. The context of this study, accurate irradiance prediction is crucial for assessing the performance of PV systems and the quantification of production.

- Performance evaluation: By considering the impact of view obstructions, the model enables more realistic evaluations of PV system performance. A simulation using this model can offer insights into how different configurations, such as row spacings and tilt angles, affect energy generation, considering a shadow ratio, allowing a better-informed decision-making in the perspective of representing real-world conditions, such as shading effects from surrounding rows.

- Projection accuracy: Accurate simulation models contribute to reliable projection of PV system output. By incorporating the thermal dynamic simulation results, along with IPCC scenario weather at an hourly scale, the accuracy of energy production will greatly be improved, aiding in storage integration and energy planning.

- Risk and uncertainty reduction: Utilizing such a complete model in digital simulations helps mitigate risks associated with PV system implementation. By providing more accurate predictions, simulations can help avoid modeling flaws or bad representation issues, ultimately reducing project risks and uncertainties.

6.2.3 Process, timeline and milestones

A Dynamic thermal simulation of both the current and future state of the airport building is studied with projections for the milestone years 2030, 2040 and 2050. Concerning the reference site state, the modeling is based on HVAC report data and historical weather data (2019) compared to measured temperature on site. Future states of the airport building are then projected on the model, considering the hypothesis on the evolution of the building in terms of passengers' staff evolution, and also on IPCC climate scenarios for the milestone years. The chosen IPPC scenario in the case of this study is the IPCC RCP2.6, which is the most optimistic scenario projection, as observed on the following graph.

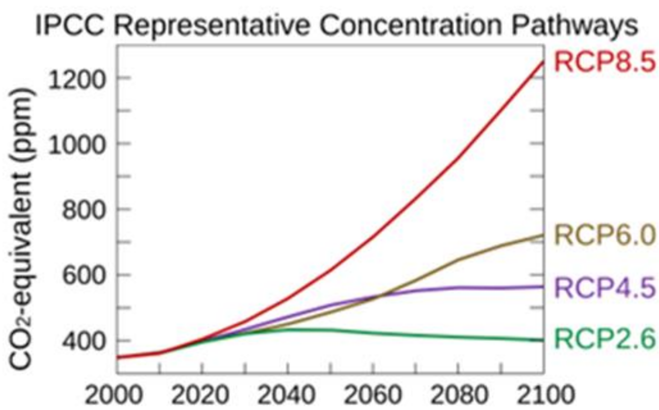


Figure 6.9, IPCC Representative Concentration Pathways

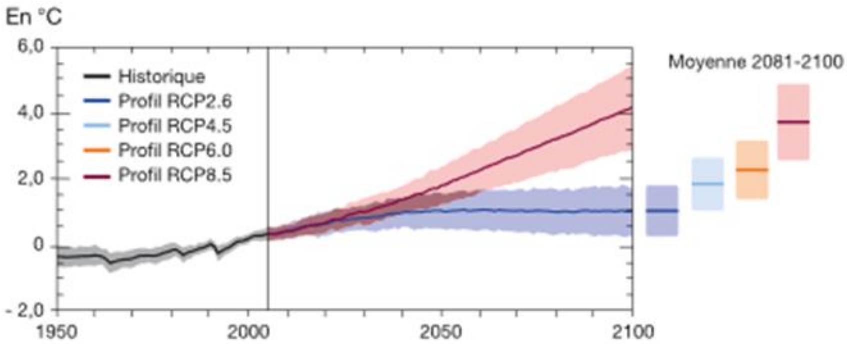


Figure 6.10, IPCC Climate Scenarios (°C)

The scenario projection limits emission such that global temperature change is contained between 0.9°C and 2.3°C rise, according to IPCC. The corresponding weather files for the milestone years show a shifting temperature distribution towards hotter temperatures as shown by the following graph.

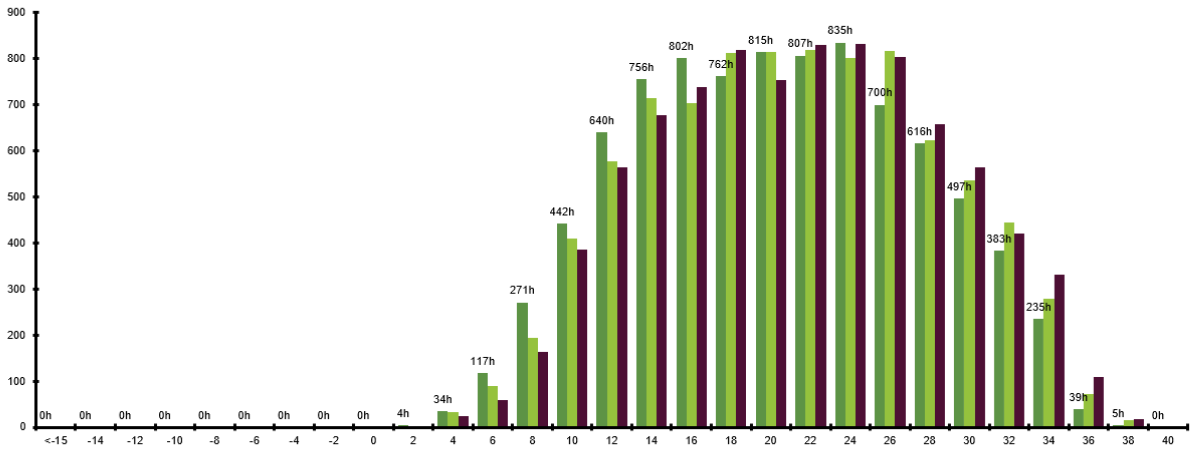


Figure 6.11, Temperature distribution for the scenario used in the simulation. X-axis, temperature, Y-axis, number of hours in year

The results of the simulation will consider the shift in terms of temperatures and the impact on the airport building consumption along with the increase in passenger and staff.

6.3 Scenarios and solution pathways

6.3.1 Introduction to the airport energy system

Cyprus energy mix is based mainly on burning of fossil fuels, thus resulting to very high emission factors. The combination of the energy mix and the isolation of the electricity grid and the lack of interconnections with other systems results to an electricity grid with very limited flexibility and specific capacities for introduction of renewable energy systems. Considering the high fuel cost of the last few years, along with the greenhouse gas taxes/cost on the electricity price makes the improvement of energy efficiency and the introduction of renewable energies for self-production a very beneficial combination.

Larnaka Airport is connected on the island's high voltage electricity grid and operates a private medium voltage grid for meeting the electricity demand of the various airport's activities.

Following the successful implementation of many energy conservation projects throughout the last decade, Larnaka Airport reduced its energy consumption by more than 35%, reaching a stage in which the energy consumption remains relatively stable. The graph below presents the reduction of energy usage combined with the significant increase in passenger traffic since 2010.

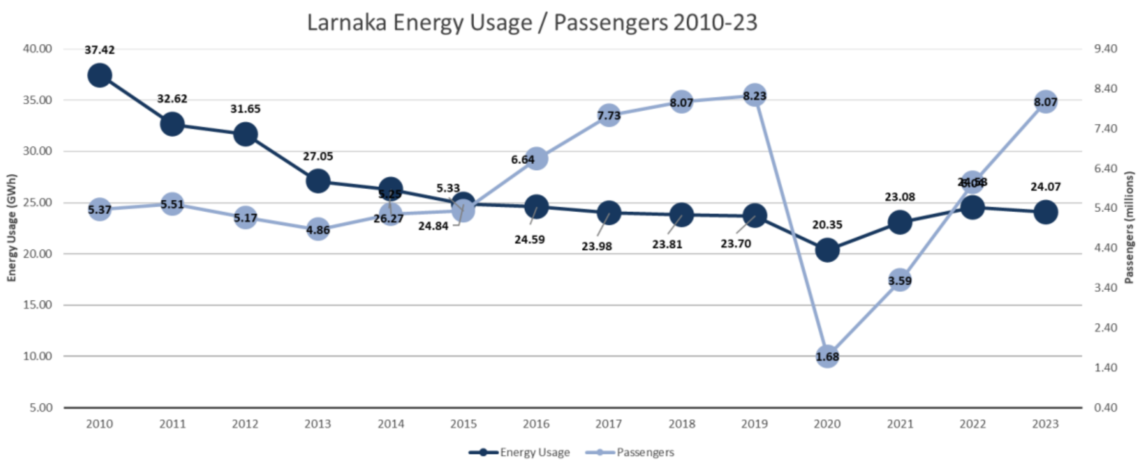


Figure 6.12, Larnaca Energy Usage and Passengers 2010-2023

In order to understand the details of the energy system and be able to identify the most significant energy usages, Larnaka Airport through a system of more than one thousand power analysers identified the various consumptions, introduced key performance indicators to monitor and set specific short-, medium- and long-term targets.

The most significant energy usages are presented in the graph below.

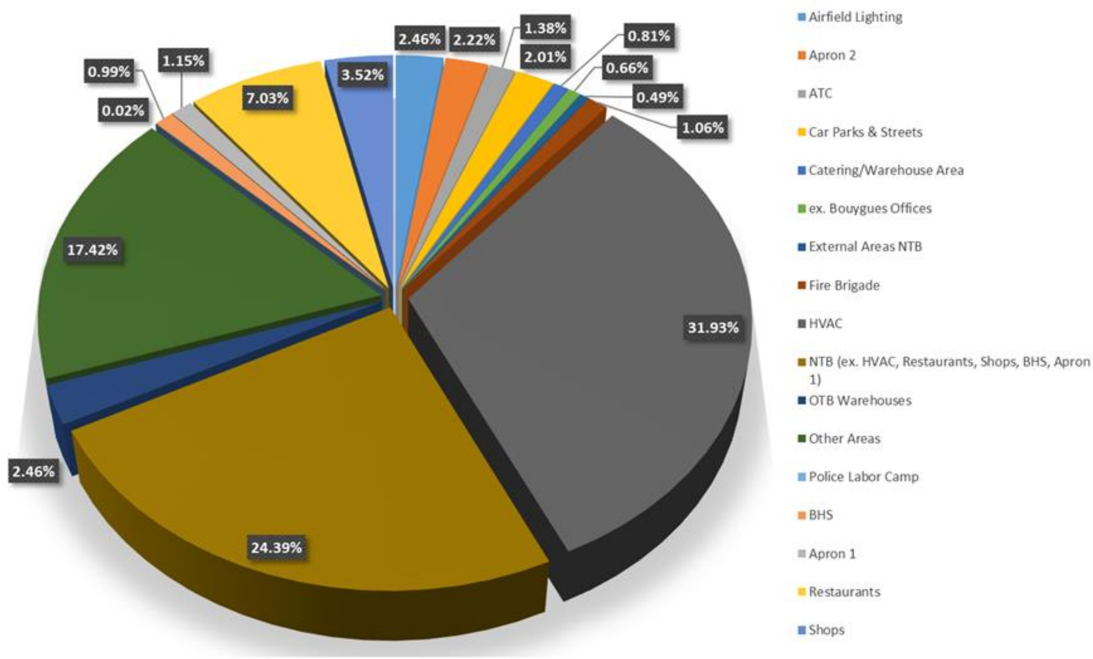


Figure 6.13, The most significant energy usages

The majority of the directly controlled carbon dioxide emissions of Larnaka Airport are related to the electricity consumption. The installation of an on-site photovoltaic plant contributed towards the reduction of those emissions. A series of actions and initiatives have been considered and added to the long-term plan and roadmap, in order to set specific medium and long term targets. The two main milestones are the Net-Zero target of 2050 and the aim for reducing all Scope 1 and 2 emissions by 96% by 2030 compared to 2010.

For this reason, the targets of emissions and electricity per passenger and per square meter of buildings are introduced to monitor the progress towards the two main targets described above Additional milestone years have been considered during the various scenarios analysis Energy system scenarios

The energy system scenarios took into consideration the following parameters:

- Passenger and Staff evolution graph
- PV evolution (from 3.5 MWp to 4.7 MWp by 2030)
- IPCC - RCP 2.6 choice justification
- Ventilation optimization (2019) 25m3/h
- Light optimization (LED + dimming)
- Temperature optimization: 24/25 °C

Other technological solutions considered amongst others are the enhancement of the existing photovoltaic plants at Larnaka Airport and the introduction of energy storage solutions, the electrification of the fleet and the ground support equipment, the modification of conventional fuel burning ground power units generators to electric ground power units and variations in the commuting. These scenarios are not studied in this report.

6.4 Modelling Framework Implementation

Detailed information on the Thermal Dynamic Modelling approach and the results of the simulation, are given in the Annex to this Report including the specifications and U values of the building surfaces, the zoning and the thermal template of the building is provided in the Annex to this Report.

Similarly for the simulation of the solar (PV) plant at Larnaka Airport and the comparison of the energy produced by the PV plant versus the energy produced needs of the terminal building.

6.5 Robust smart energy hub concept(s)

6.5.1 Robust smart energy hub concept(s)

The simulation also examined the alignment between the demand for energy and the PV production at Larnaca International Airport using the actual existing PV plant characteristics and the terminal building thermal envelop and demonstrated that most of the time the PV energy could be usefuly used. In practice though the actual PV production has been curtailed (restricted) by the national grid operator on the premise that the national grid cannot absorb the excess energy produced by the PV plant and the problem is that the curtailment applied is much greater to the extent that it cuts off energy that would have been beneficially used by the airport.

Consequently, Larnaka Airport as a first step is considering the implementation of a robust smart energy hub to self-regulate PV production so it matches the airport's demand for energy, and thereby not generating any excess energy, thus preventing the national grid from interfering and cutting the energy produced by the PV plant. As a second step the airport will consider the introduction of battery storage for excess energy produced by the PV plant. This approach will ensure that all solar energy generated is used locally within the airport, minimizing the need to export surplus energy to the grid and reducing the impact of grid regulation constraints. To achieve this, Larnaca Airport is planning to implement an advanced smart energy control system that dynamically manages the generation, storage, and consumption of solar power.

The smart energy control system is designed to optimize the PV park's output by intelligently balancing supply and demand, thereby preventing excess energy from being exported and aligning with the zero-export policy. The system will adjust energy flows and storage operations, ensuring that the airport's energy needs are met efficiently and sustainably.

In addition to supporting zero export, the control system enhances the resilience and flexibility of the airport's energy infrastructure. It facilitates the seamless integration of renewable energy sources with existing energy systems and incorporates energy storage solutions to buffer against fluctuations in supply and demand. This comprehensive approach not only contributes to reducing greenhouse gas emissions but also advances Larnaca Airport's sustainability goals by promoting self-sufficiency and reducing reliance on fossil fuels.

Overall, the robust smart energy hub at Larnaca Airport exemplifies a forward-thinking model for sustainable energy management in aviation, positioning the airport as a leader in adopting innovative and environmentally responsible practices.

6.6 Conclusion

Dynamic simulation modelling has been used to identify and quantify potential energy conservation measures at the Terminal Building at Larnaka International Airport, of the energy produced by the onsite photovoltaic (PV) plant for three milestone years, 2027, 2030 and 2040 and the simulation also examined the alignment between the demand for energy and the PV production. The analysis performed is relevant to the operation of Larnaka Airport and particularly to Hermes' Climate and Energy Road map.

Energy conservation and PV production are among the core measures included in Hermes Climate and Energy Road map to net zero, hence the decision to perform these simulations is consistent with the Energy Strategy of Hermes Airports and of Larnaka International Airport.

The thermal simulation modelling has identified that increasing natural ventilation during certain months and during specific hours of the day is an effective method to reduce electrical energy consumption by the HVAC systems without detrimentally affecting thermal comfort conditions for passengers and staff. Similarly, the simulation has shown that solar shading and increasing the set point temperature within the conditioned spaces of the airport also will yield significant energy savings. It was not within the scope of the thermal simulation modelling however, to consider the practical aspects of increasing natural ventilation and how to treat the fresh air before it is delivered into the Terminal, or the practical aspects of adding solar film and how the reduction of daylight would impact the perception and satisfaction of the customers.

The simulation demonstrated that a high level of self-consumption of Solar PV is possible when the plan is operating at full capacity and during periods when production exceeds the demand from the Terminal, the excess production could be used for charging electrically driven vehicles and ground service equipment operating at the airport. However, real life experience has shown that the national grid operator intervenes and applies curtailment i.e. cuts the PV production because the national grid cannot absorb the excess energy produced. The curtailment applied however is much greater than the excess energy produced by the PV plant and Larnaca Airport loses energy that would have been beneficially used. For this reason, as a first step to be implemented in the short term, it is planned to introduce a local smart energy system that will self-regulate PV production to match the energy demand of the airport and thereby prevent the national grid from externally accessing the PV plant and applying curtailment, while as a second step battery storage will be assessed for the excess energy produced.

With the help of the model Larnaca identified a huge potential to decrease the energy demand for cooling, without however examining the practical challenges of doing so or the impact on the passenger perception and experience. The latter was outside the scope of the simulation.

Regarding the energy production by the photovoltaic plant at Larnaka Airport the simulation has identified that during certain times of the year the energy produced can cover the needs of the Terminal building for electricity. Also, there will be certain periods when PV energy production exceeds the energy requirements of the Terminal Building, and battery storage would be an option during those periods.

The excess energy produced by the PV plant and stored in the batteries could be used to charge electrically driven vehicles and ground service equipment operating at the airport.

Within the concept of the Smart Energy Hub, the information provided by the thermal modelling and PV production modelling could be used by Hermes to specify the performance requirements for and advanced energy management system and support decision making with regards to when to use each available source of energy from the mix available.

7 General reflections and conclusions

The transition of airports from traditional fossil-based energy sources to more sustainable energy solutions implies the transformation of all energy demanding units such as buildings, vehicles and airside supporting equipment. This transformation will inevitably affect the energy demand requiring a modification on the existing energy grid also considering that intermittent renewable energy sources will be more and more present inside airports. The creation of a smart energy hub enables the airport to efficiently utilize renewable energy sources produced on site and coming from the external grid and to optimise the infrastructure through load-shifting, sector-coupling and storage. This system should encompass all generation assets, infrastructure and energy needs such as electricity, heat and cold, hydrogen, biogas and other fuels.

This study conducted modelling activities to draw insights on the implementation of a smart energy hub at an airport. At first, the current and (expected) future energy needs and available technologies were determined. Then, several scenarios were developed to explore the impact on the airport's future energy demand. Modelling and simulation of the various scenarios enabled the exploration of different technological pathways thus allowing to obtain different insights that can support the sustainable airport transition and that can be applied to other airports.

7.1 Reflections on differences between airports as smart energy hubs

The four different airports analysed in this study differ in the context in which they operate. This imposes boundary constraints and enables or disables the adoption of specific technological pathways. In the following paragraphs the main factors affecting the technological choices are highlighted.

Geographical context. The latitude at which the airport is located affects significantly first of all the composition of the primary energy demand of the airport. As easily predictable, for northern airports' the weight of heating is more relevant if compare to southern regions, at the same time the cooling demand has a behaviour that is opposite. Since cooling demand synchronizes quite well with solar PV production but heat demand during winter periods does not, the airports specific energy need has a strong impact on the potential of certain technological solutions. Consequently this implies an easier access to electrification enablers for southern airports and a need of a wider range of options needed for airports with a significant heating demand.

National energy context. The availability of renewable resources can differ largely between the regions where the different airports operate in. In southern regions the PV plants are a more viable option both for on-site production (thanks to the high amount of equivalent hours) and for the purchase of green electricity from the grid, for northern airports a wider range of choices is present in particular thanks to the larger availability of wind plants and in some cases to the presence of larger amounts of biomass resources (both solid and through transformation in biomethane).

Size of the airport. The composition and scale of airport operations are crucial to the design of a smart energy hub. The presence of a large share of short haul flights combined with the possibility to operate smaller commercial aircrafts in northern regions implies the concrete possibility of having in the short term a large amount electric flights, thus implicating the need to supply and manage larger amounts of electricity at high power rates. For other airports the electrification of flights could be slower and less impacting, while at the same time the demand of hydrogen over time could be a variable to be taken into account.

The size of the airport also affects differently the operations, the type and amount of energy needed to meet decarbonisation targets: larger airports encounter difficulties in electrifying entirely GSE activities and need a wider range of options, while for smaller regional airports thank to a more compact geometry of the terminal the electrification of ground operations could be easier to be achieved.

7.2 Reflections on commonalities between airports as smart energy hubs

Although the smart energy concept introduced in the four studies differ in scope, all successfully employ smart grid strategies to meet energy demand and supply. Some common strategies have been identified and summarised below.

Energy efficiency. The reduction of primary energy supply is a cornerstone to achieve net zero targets and optimise the use of energy inside complex energy systems as airports are. Even if the increasing of energy efficiency is a pathway that has been followed by all the airports through the last years, there is still room for improvement and optimisation of the energy demand thus reducing the impact of the increasing demand of energy related to the transformations needed. At the same time reduction of primary energy demand releases part of the power used on existing electrical cabinets, reducing the need of new installations.

Electrification. From the analysis conducted, electrification of the energy demand is considered one of the most effective and resilient pathways to reach the net zero target. This can be developed both on the heating demand when lower grade renewable sources are not available and on airside operations with the effect of reducing the demand of fossil fuels and increasing the electricity demand accordingly. This phenomenon is already taking place at a faster rate than expected but is currently slowed down by limitations of the available grid capacity from DSO/TSO's (congestion) at most airports involved. The future airport smart energy hub is expected to be complex and demanding to manage. Airports expect that to do this properly each airport needs to have the full ownership of the airport grid infrastructure.

On site production and storage. All airports introduce electricity generation on site, mostly in the form of solar PV: this is considered as a feasible way to decarbonise and at the same time to reduce grid dependency. In order to match the internal demand with the production and reduce as much as possible the export of energy exported to the external grid, all airports will consider different storage solutions. Other actions in this direction regard load shifting and peak shavings at cabinet level in order to match demand and renewable electricity production and to reduce congestions on the internal distribution grid. Another possibility proposed is related to smart charging devices that can enable airports to shift demand to periods of high renewable electricity production or alleviate infrastructural requirements.

Diversification of energy resources. A complex problem has to be faced with different solutions concurring to achieve the common goal of decarbonisation: diversification of energy streams (as for example hydrogen or biomass) can decrease infrastructural limitations even if at the same time can increase the airports dependency on external partners.

The regional energy infrastructure is often the limiting factor for the rate at which the transition of the airport is possible. Hydrogen, as a particular instance of external energy supply, will require the establishment of a dedicated infrastructure connecting the airport to hydrogen producers. The volume of hydrogen required by the airport for power generation purposes alone would likely be too small to justify significant investments in transport infrastructures over long distances. For a transition to a hydrogen infrastructure a concerted effort of the airport with local stakeholders towards the realization of a local hydrogen economy would be needed. Based on the studies, the deployment of H2 is not expected before 2030, potentially in the ’40s.

A similar argument can be applied to biomethane even thus in this case the geographical context and the number of potential off takers is even more relevant for its availability at airports.

7.3 Elements of the future airport smart energy hub

The following cornerstones of the development of a smart airport energy hub were identified:

Optimisation of existing infrastructure. The study shows that a considerable part of the growing energy demand at the airport can be compensated by efficient utilisation of the available local resources. In particular this applies to two aspects of the energy system. First of all to the existing electric infrastructure: the transformation required implies a growing electrical demand, and not always it will be possible to extend the existing distribution infrastructure. The optimisation of the existing cabinets will be crucial to create a resilient energy system not modifying in a substantial way the actual configuration of the system.

In second place, the utilisation of the available area at the airport for the installation of renewable plants will foster the decarbonisation pathway. The areas surrounding airports often are not used for any other purpose, thus the deployment of local renewable generation systems does not create additional significant impacts for the communities that share the surrounding environment. This situation is probably common for a lot of airports, and this experience present an high level of replicability.

Increased self-sufficiency. Independently on the chosen technological pathway, a radical shift of the airport from the current *energy consumer* to *energy "prosumer"* role is expected and should be a pivotal part of the Airport energy strategy. This will allow to increase the resiliency of the energy system and at the same time to reduce the local based emissions.

Exploitation of resources available locally. The study showed that the specific features of the geography and energy context in which the airport is located heavily influence the choices that can be made. In this sense, it is therefore important to emphasize the importance of exploiting as much as possible the opportunities that the local communities provide, thus increasing the synergies with the territory in order to create a smart energy hub that is closely integrated with the needs of the area.

Diversification of resources and sector coupling. Another constant of each strategy investigated lies in the increased complexity of the energy system. Under the current configuration of the airport, different energy sectors are compartmentalised and associated with specific energy carriers. The transformation required implies the creation of a sustainable, integrated energy system. The right energy mix will include: deployment of sustainable resources, energy storage systems to match supply and demand, smart charging and discharging facilities with H_2 as possible back-up system, for large scale vehicles.

Deployment of new technologies requires **long-term strategic approach**. New safety requirements (from an operational and permit standpoint) and risk based analysis need to be considered. Critical success factors like energy markets (size), geographic aspects, supply chain factors, workforce (availability of workforce with critical skills) need to be included, a human capital agenda is needed. The choice between on-site generation and market-based solutions needs strategic planning. Managing and operation of the local grid can be very demanding, especially when electric planes are introduced. To support the long-term strategy, dynamic modelling of energy needs can be useful, as it helps identifying the correct energy demand, how improved energy efficiency can impact the energy requirements, where and how electricity demand can be met by PV plants, and when and how much battery capacity is needed. These models can guide the decision making.

Modelling can help finding weak points and bottle necks of the infrastructure, suggesting solutions to reinforce the system thus anticipating problems occurring and potentially impacting the operation of the airport.

Need for external green energy supplies. Even if increasing the self-sufficiency of the airport s is one of the milestones of all energy strategies adopted, the analysis revealed that the realisation of an energetically autarchic system would be hard to achieve from an economic perspective. External supplies of green gases, either biomethane or hydrogen, and decarbonisation of the regional electricity grid represent a fundamental enabler of the energy transition of the airport.

Correct evaluation of risks. The study showed that, given the various radical changes that will take place in the aviation sector in the coming years, there are technological changes that will heavily impact the airport energy system. In this regard, it is critical to properly weigh the impact of operational changes such as the electrification of GSEs and the potential additional energy demand associated with the diversification of aircraft power sources (in particular electrification and on the long-term hydrogen). These changes will lead to an evolution of the role of the airport, which will have to be increasingly integrated with handling and aircraft refuelling activities, in order to be responsive to all emerging demands related to the transformation of airports.

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8 Annex 1: Introduction to TULIPS

Amsterdam Airport Schiphol (lighthouse airport) and its fellow airport partners Avinor in Oslo, Hermes at Cyprus and SAGAT in Torino will be the proving ground for 17 demonstrator projects that result from the collaboration. Figure 8-1 below presents the TULIPS overall concept, summarising the needs of airports in general and Amsterdam Schiphol and its shareholders in particular, the project activities and the central role of the demonstrators. The project has been designed considering the robust project drivers that exist. The expected results of the projects are listed as well as the future impact that these will have once they are upscaled, commercialised and deployed across European airports.

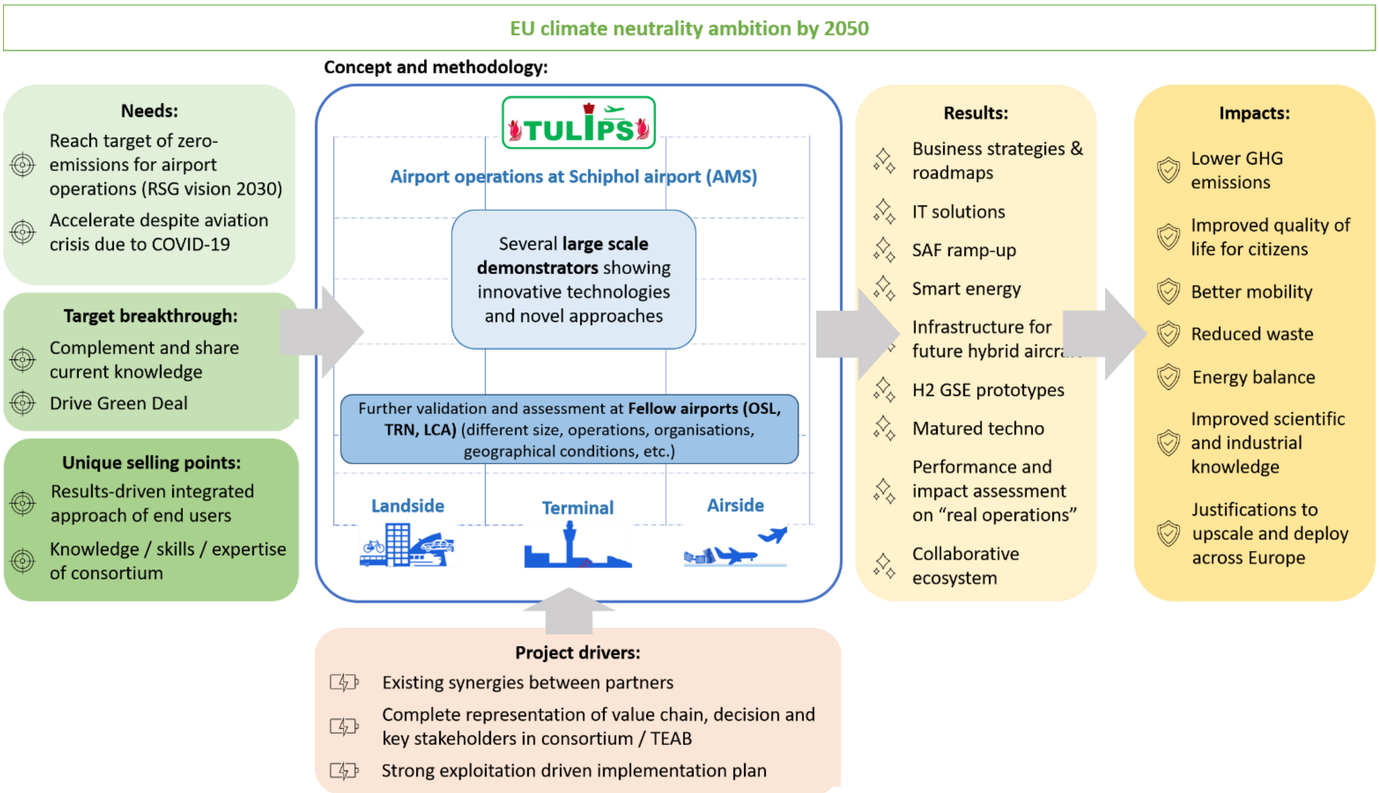


Figure 8-1 Overall concept TULIPS

A full transition to sustainable (local) energy production and usage for all energy demanding units (buildings, vehicles and supporting operating equipment such as moving staircases) implies a higher energy demand flowing through the existing electricity grid and more fluctuations as renewable energy resources (like wind and solar) are strongly dependent on weather conditions. This fact justifies the need to design and start implementation of a smart resilient energy system at the airports. Such a system includes energy infrastructure with intelligence and will encompass all energy needs, energy assets (e.g., distribution system, storage, conversion systems) and energy production facilities like electricity, heat and cold, H2, biogas and fuels. The system should be fit and efficient for the current as well as future supply and demand needs. A major emphasis has to be given to the existing and future control system that should be evolved to an integration, monitoring and control system that is able to manage all energy transport at airports during and after the transition towards their sustainable future.

8.1 Introduction to Amsterdam airport Schiphol

8.1.1 General introduction of Schiphol airport

Royal Schiphol Group (RSG) is the owner and operator of Amsterdam Airport Schiphol, Rotterdam The Hague Airport and Lelystad Airport, and holds a majority stake in Eindhoven Airport. Airports in the Group create value for society and for the economy, with safety as a key enabler. Together with Schiphol Group’s international activities, Schiphol Group's Dutch airports are part of the 'Why' of Connecting your world.

Connecting the world embodies the 'Why' of Royal Schiphol Group. By creating the world's most sustainable, high quality airports Schiphol Group allows international trade, tourism and knowledge exchange to flourish by providing top-quality aviation infrastructure and air transport facilities for passengers and cargo.

By ensuring optimal air connectivity for the Netherlands, we are supporting the economy while also helping to promote the traditional Dutch values of openness, tolerance and international-mindedness for which we are known around the world. Schiphol Group does this with the support of many partners across the aviation sector and beyond.

Schiphol Group's ambition is to operate the world's most sustainable, high-quality airports. It is the leading member of the TULIPS consortium, which brings together 29 parties in the aviation chain to accelerate sustainable aviation. Schiphol Group wants its operations to be zero-emissions and zero-waste by 2030 and to function as an energy-positive and fully circular organisation by 2050. Equally important, Schiphol Group will continue to play a leadership role in driving sustainability across the aviation sector, aiming for net- zero carbon emissions aviation by 2050.

Achieving the long-term ambitions of Schiphol Group will depend on its ability to adapt to its much-changed operating environment and the many logistical and economic challenges this brings. The top priority now is to redress the balance and re-establish Schiphol Group’s reputation as a leading international airport. Schiphol Group will also take advantage of this opportunity to make Schiphol a more sustainable place to work.

Schiphol Group is determined to continue doing its part to help create a world connected by sustainable aviation. This is reflected in its involvement in the TULIPS consortium to accelerate innovations for a more sustainable aviation industry, to participating in Destination 2050, a Europe-focused roadmap towards net-zero aviation, the International Air Transport Association (IATA)'s commitment to achieving net-zero carbon emissions by 2050, and the Fit for 55 package.

8.1.1.1 Vision 2050

Royal Schiphol Group's Vision 2050 is setting a new and aspirational goal for its organisation and the wider Dutch aviation industry. Schiphol Group's Vision is based on strengthening the fundamental 'qualities' it offer as a group: Quality of Network, Quality of Life and Quality of Service. Safety and a Robust organisation are the two key enablers that support the 'qualities'.

8.1.2 Airport business scenarios

The airport business scenarios are based on the reference forecast for the development of aviation in the Netherlands. The AEOLUS aviation reference forecast 2022 is a long-term forecast for 2030 and 2050. AEOLUS is a global and strategic simulation model that can be used to calculate how the aviation industry in the Netherlands is likely to evolve. The key objective of the AEOLUS model is to provide insights in developments over the long term. The base year of the model is 2017, and the main forecast years of the model are 2030 and 2050.

Based on certain economic development scenarios, the model can calculate for Dutch airports:

- number of air passengers (passengers can be broken down by travel motive, origin, destination and flight route);
- the amount of air cargo;
- and the number of air transport movements.

Based on the number of aircraft movements, in terms of impact on the environment, the model can calculate estimates for:

- impact on global CO2 emissions;
- impact on local LTO emissions;
- number of homes within the 58 dB(A) Lden noise contour around Schiphol.

For the different forecasting scenarios, only current policies have been taken into account. This means that for Schiphol Airport this means that there is a maximum number of 500,000 aircraft movements per year. Based on these constraints, AEOLUS provides two scenarios for economic development: high and low. Both scenarios assume that there will not be any lasting effects from the COVID pandemic in 2030 and 2050. Furthermore, it is expected that in both scenarios, the maximum capacity of 500,000 movements per year is reached in 2030 and 2050. Despite the limits to growth, it is still expected that passenger numbers will increase due to larger flights that operate at higher load factors.

8.1.2.1 Business model Schiphol Group

The Business model of the RSG is based on the UN model to achieve positive outcomes and a positive impact on wellbeing and prosperity and the UN Sustainable Development Goals, 5 Gender Equality, 7 Affordable and Clean Energy, 8 Decent Work and Economic Growth, 9 Industry Innovation and Infrastructure, 11 Sustainable Cities and Communities, 12 Responsible Consumption and Production, 13 Climate Action and 16 Peace Justice and Strong Institutions **Error! Reference source not found.**.

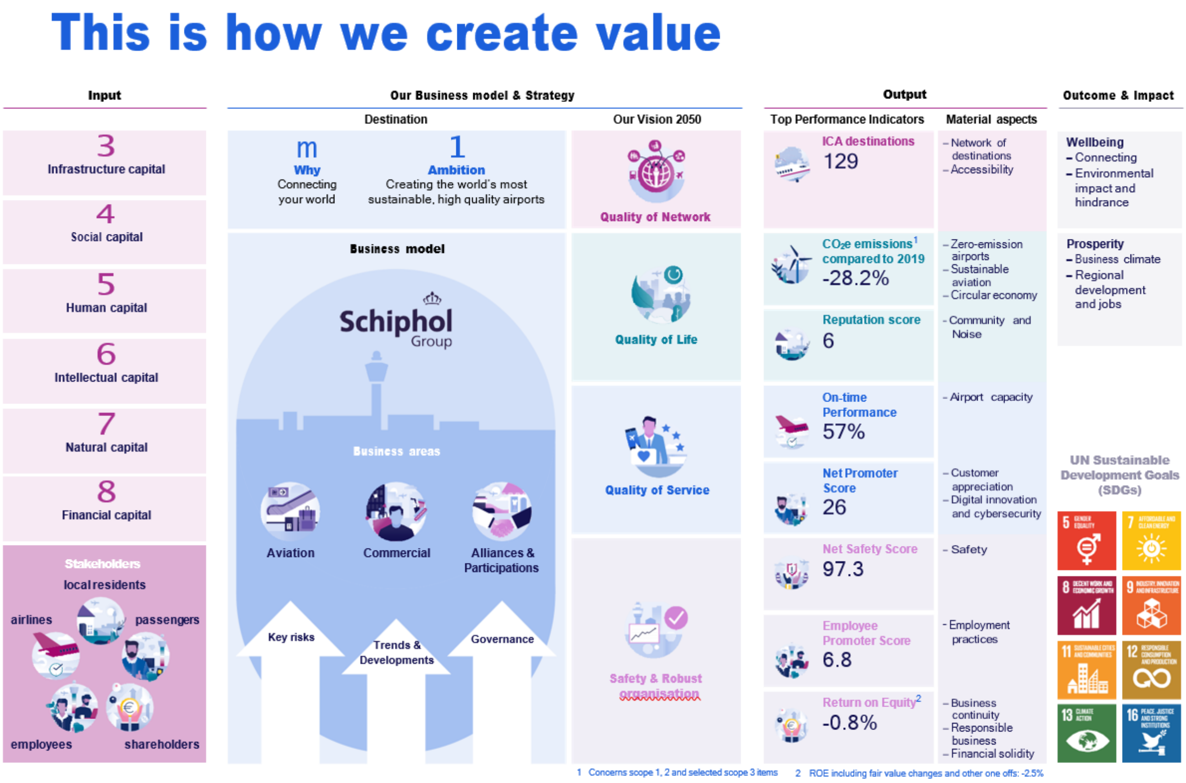


Figure 2 Royal Schiphol Group Business Model

We reflect on the material aspects that relate to Royal Schiphol Group in line with the Global Reporting Initiative (GRI) guidelines, which indicate that an aspect is material when it influences the decision-making of our stakeholders or reflects a significant potential financial impact on our organisation. Our value creation model depicts the relationship between our material aspects, strategy and risks. For a more detailed description we refer to the RSG annual reports.

An important condition of the RSG business plan is that it meets the requirements of a sound financial policy and is robust enough to weather potential financial setbacks. The business plan also results in a management agenda, which sets out concrete actions and targets for management for the year ahead. Since 2019, Schiphol Group's target setting has consisted of the Top Performance Indicators (TPIs) and major deliverables, enabling the introduction of a consistent language across Schiphol Group, the alignment of all Group activities and a focus on the most value-adding activities. The major deliverables are grouped in three clusters: strategic, tactical and operational.

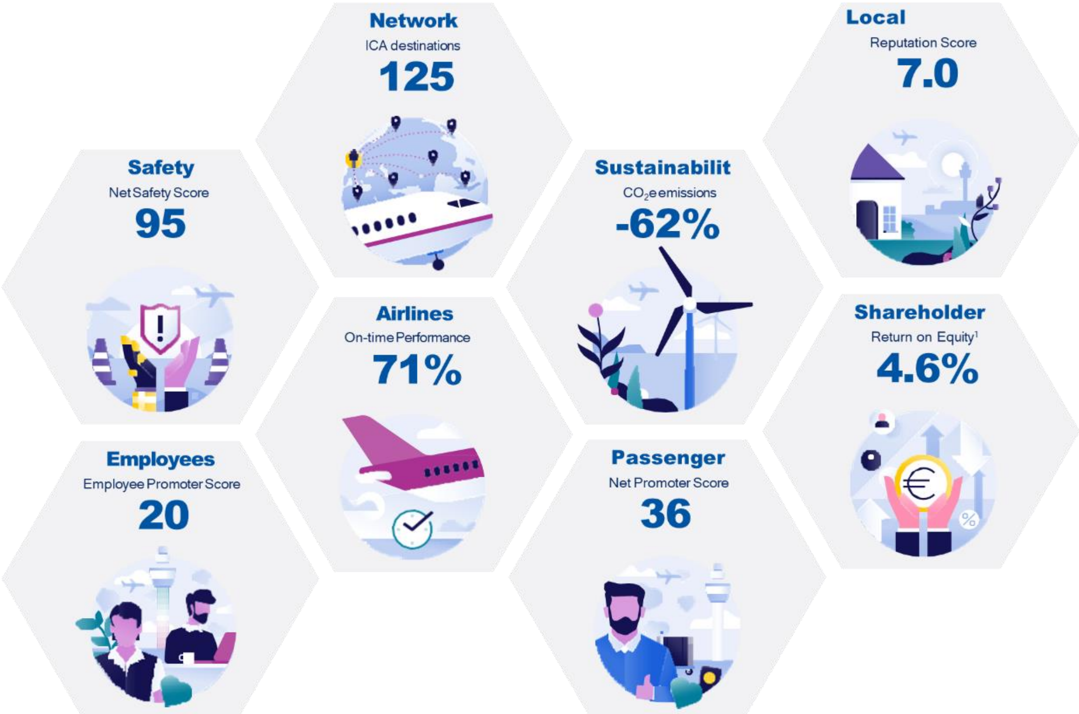


Figure 3 Top Performance Indicators Royal Schiphol Group 2023

A description of the target setting of Top Performance Indicators of the year 2023 is given in the frame below.

TPI targets for 2023

Priorities

Safety
Net Safety Score target 2023: 95
This index takes into account the percentage of days without serious[1] incidents minus the percentage of days with serious incidents[2].

Sustainability
CO_2e emissions Royal Schiphol Group target 2023: -62%[3]
Decrease in CO_2e emissions compared with 2019 levels, taking into account Scope 1 (natural gas and fuels used by own vehicle fleet) and selected items of Scope 3 (natural gas used by third parties in buildings owned by Schiphol Commercial with their own environmental permits, airside fuels, commuter traffic and business travel by own car or aircraft[4]). Please note that the definition has slightly changed compared with previous year. A switch has been made from location-based emissions to market-based emissions without Scope 2 (electricity), since Schiphol Group purchases 100% renewable electricity and the market-based method therefore better reflects our progress towards zero emissions in 2030.

Network
Number of intercontinental destinations target 2023: 125
The number of direct intercontinental destinations for passengers and cargo[5].

Passengers
Net promoter score target 2023: 36
The Net Promoter Score (NPS) measures how likely passengers are to recommend Schiphol as an airport. Customers are asked: 'On a scale of 0 to 10, how likely would you be to recommend this airport to friends, family and colleagues?' Passengers who give a score under or equal to 6 are detractors; 9 or 10 are promoters. The score is determined by subtracting the percentage of customers who are detractors from the percentage who are promoters. The result is a score between -100 and 100[5].

Airlines
On-time performance target 2023: 71%
The punctuality of outbound traffic is the percentage of commercial flights departing on time (based on the sector wide standard D15)[5].

Local residents
Reputation score target 2023: 7.0
This score is based on reputation surveys and the number of people who have filed one or more reports at Bewoners Aanspreekpunt Schiphol (BAS). The reference for BAS is a 24-month rolling average[5].

Employees
Employee Promoter Score target 2023: 20
The Employee Promoter Score (EPS) measures how likely employees are to recommend Schiphol as an employer. Employees are asked: 'On a scale of 0 to 10, how likely would you be to recommend your employer to friends and acquaintances?' Employees who give a score under or equal to 6 are detractors; 9 or 10 are promoters. The Employee Promoter Score is determined by subtracting the percentage of employees who are detractors from the percentage who are promoters to generate a score between -100 and 100, which is similar to the Net Promoter Score[5].

Shareholders
Return on equity (ROE) *targets 2023: 4.6%*
Financial return for shareholders based on net result adjusted for fair value gains and losses on investment property and one-off items divided by average equity[6].

1 Serious incidents are defined as incidents that have led to death, permanent injury or hospitalization and potential fatal incidents (near miss).
2 The scope of this TPI is Amsterdam Airport Schiphol and contractors.
3 The 2019 baseline is 160kt CO_2e.
4 The scope of this TPI is the Dutch airports of Schiphol Group.
5 The scope of this TPI is Amsterdam Airport Schiphol.
6 The scope of this TPI is Royal Schiphol Group.

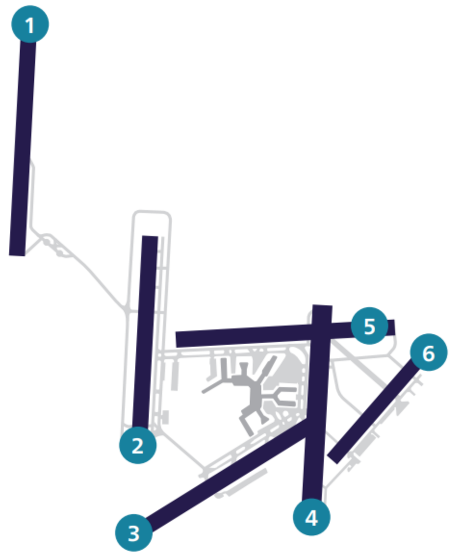
Figure 4 Top Performance Indicators Description Royal Schiphol Group

8.1.2.2 Key facts and Figures of Amsterdam Airport Schiphol

Operating Schiphol is one of Royal Schiphol Group's main activities. Amsterdam Airport Schiphol, commonly known as Schiphol Airport, is the main international airport of the Netherlands, located southwest of Amsterdam in the municipality of Haarlemmermeer. It is one of the busiest airports in Europe in terms of passenger traffic and is a major hub for international travel.

Schiphol employs a one-terminal concept, consolidating all facilities under a single roof, radiating from the central plaza. The terminal is divided into three sections, namely Departure Hall 1, 2 and 3. Travelers can navigate between piers and halls on both sides of security or border inspection, although border control separates Schengen from non-Schengen areas. Schiphol has six runaways as shown in Figure 8-6. The airport hosts 222 aircraft stands of which 91 are connected to the halls.

Runways



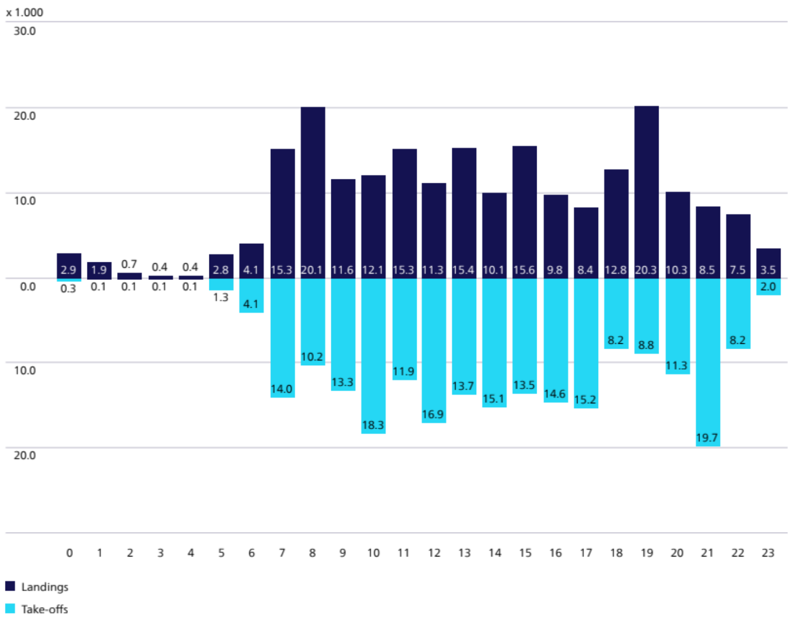
Runways	Location	Length	Width
1 Polder Runway	18R - 36L	3,800 metres	60 metres
2 Zwanenburg Runway	18C - 36C	3,300 metres	45 metres
3 Kaag Runway	06 - 24	3,500 metres	45 metres
4 Aalsmeer Runway	18L - 36R	3,400 metres	45 metres
5 Buitenveldert Runway	09 - 27	3,453 metres	45 metres
6 Schiphol East Runway	04 - 22	2,014 metres	45 metres

Figure 5: Schematic representation of Schiphol airport's runways

Schiphol Airport has convenient transportation connections with train services to Amsterdam Central Station and other major cities in the Netherlands, as well as bus and taxi services.

Currently, Schiphol Airport has a direct connection to 305 destinations operated by 97 airlines. In 2023, 441969 air transport movements were mad. The majority of landings and take-offs take place between 7.00 and 19.00 as shown in Figure 8-7. Of the total number of air transport movement, 96.4% where passenger aircraft movements.

Per hour of the day



		Landings	Take-offs	Total
Night	23:00-05:59	12,478	4,073	16,551
Early morning	06:00-06:59	4,103	4,050	8,153
Day	07:00-18:59	157,768	164,915	322,683
Evening	19:00-22:59	46,631	47,951	94,582
Total		**220,980**	**220,989**	**441,969**

Figure 6: Average daily passenger distribution at Schiphol Airport

In 2023, 61.9 million passengers travelled via Schiphol Airport distributed over the year as shown in Figure 8-8. Of the total number of passengers, 63.7% where origin and destination passengers. 70% of the total number of passengers had a destination within Europe.

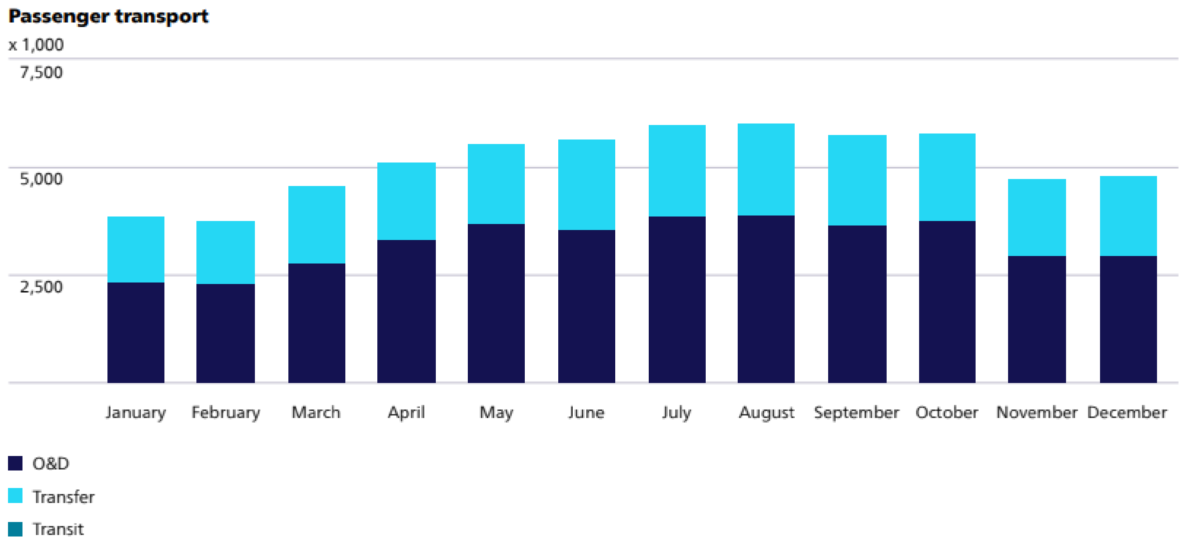


Figure 7: Annual distribution of passengers with total number of O&D, transfer and transit passengers

In 2023, 1.38 million tonnes of cargo was processed through Schiphol. The main part of cargo was transported via full freighter movements of which 15969 were made in 2023. The remaining 0.5 million tones of cargo was transported on passenger aircrafts.

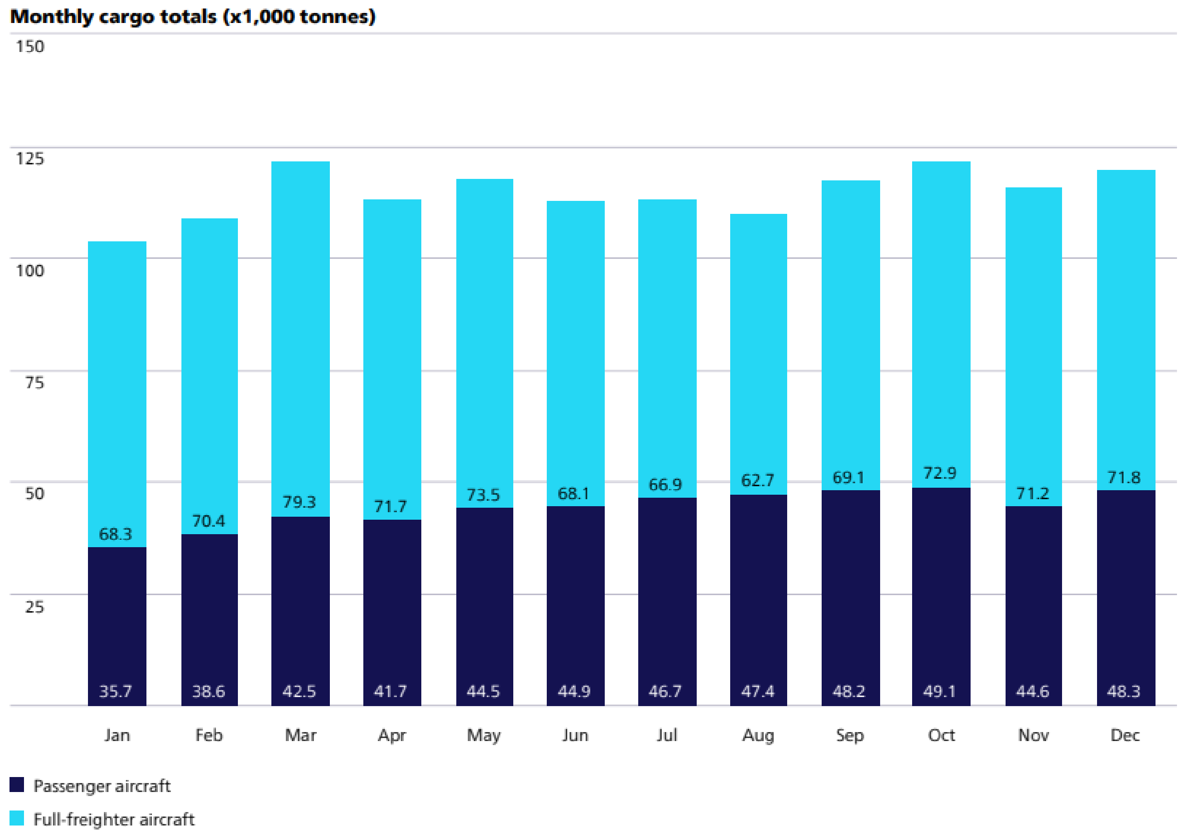


Figure 8: Annual distribution of cargo per month divided over passenger aircraft and full-freighter

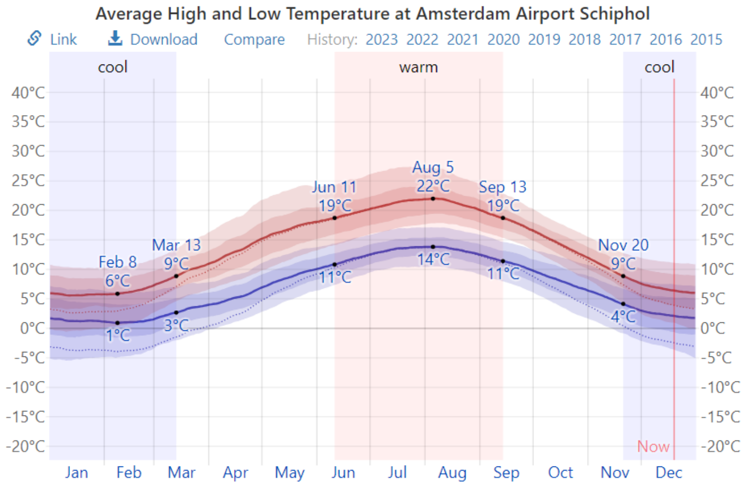
8.1.2.3 Climate and Average Weather

At Amsterdam Airport Schiphol, the summers are comfortable; the winters are generally long, (very) cold, and windy; and it is partly cloudy year-round. Over the course of the year, the temperature typically varies from *1°C* to *22°C* and is rarely below *-5°C* or above *27°C*.

Average Temperature at Amsterdam Airport Schiphol

The warm season lasts for 3.1 months, from June 11 to September 13, with an average daily high temperature above 19°C. The hottest month of the year at Amsterdam Airport Schiphol is July, with an average high of 21°C and low of 13°C.

The cool season lasts for 3.8 months, from November 20 to March 13, with an average daily high temperature below 9°C. The coldest month of the year at Amsterdam Airport Schiphol is January, with an average low of 1°C and high of 6°C.



The daily average high (red line) and low (blue line) temperature, with 25th to 75th and 10th to 90th percentile bands. The thin dotted lines are the corresponding average perceived temperatures.

Average	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
High	6°C	6°C	9°C	13°C	17°C	19°C	21°C	21°C	18°C	14°C	10°C	7°C
Temp.	3°C	4°C	6°C	9°C	13°C	15°C	18°C	18°C	15°C	11°C	7°C	4°C
Low	1°C	1°C	3°C	5°C	9°C	11°C	13°C	13°C	11°C	8°C	5°C	2°C

© Source https://weatherspark.com/

Figure 9 Overview of Average Temperature for Amsterdam Airport Schiphol

8.1.3 Royal Schiphol Group footprint and ambitions

The long-term goals for the Royal Schiphol Group are to become Net Zero by 2030 and Energy Positive in 2050.

In 2019, Schiphol Group introduced Top Performance Indicators (TPIs), including a sustainability TPI with the aim of monitoring our progress towards our 2030 zero-emissions goal. We aim to ensure that our own operations are zero-carbon and zero-waste by 2030, which means we aim to achieve a 100% reduction for our Scope 1 and 2 emissions. These targets are well ahead of the UNFCCC Paris Agreement and the Dutch Climate Act.

Table 1 KPI Paris Proof Indicators

Indicator	
Performance Indicator	Schiphol
Final energy demand [GWh/a]	250.7
Total energy supply [GWh/a]	
Final energy demand offices (kWh/m2)	145
Final energy demand Terminal buildings (kWh/m2)	236
Final electricity demand demand Cargo buildings (kWh/m2)	76
Final gas demand demand Cargo buildings (kWh/m2)	105

Our Scope 3 emissions include Ground support equipment, commuter traffic and business travel own employees .

Energy-positive own buildings

As buildings and assets fall within our direct sphere of influence (Scopes 1 and 2), we place strong emphasis on improving their energy performance. We have an energy-efficiency programme in place for existing buildings and assets, with a year-on-year energy reduction target of at least 4% at our airports.

Energy positive

Our pathway towards our energy-positive goals includes:

- Energy-positive own buildings: phasing out natural gas and improving energy efficiency;
- Zero-emissions mobility: phasing out fossil fuels for own vehicle fleet and for ground-support equipment;
- Renewable energy: solar power generation at own airport locations.

Energy principles

Our way of working is based on the Trias Energetica approach:

- Reduce the use of energy and fossil fuels;
- Use energy as efficiently as possible;
- Produce and use renewable energy to replace fossil energy.

We began this process in 2009 when we initiated carbon emissions mapping and monitoring.

Building upon these insights, we have categorised our reduction measures in terms of buildings, mobility and renewable energy. Many airport activities, such as ground handling, are operated by third parties. This situation complicates carbon management, since many of the emission sources are outside the direct control of the airport operator. As such, other airport users, including airlines, concessionaires and ground handlers, play an important role in reducing overall emissions at airside and landside. Schiphol Group employs an energy management system that is ISO 50001-certified for our four Dutch airports and closely monitored as part of our sustainability governance.

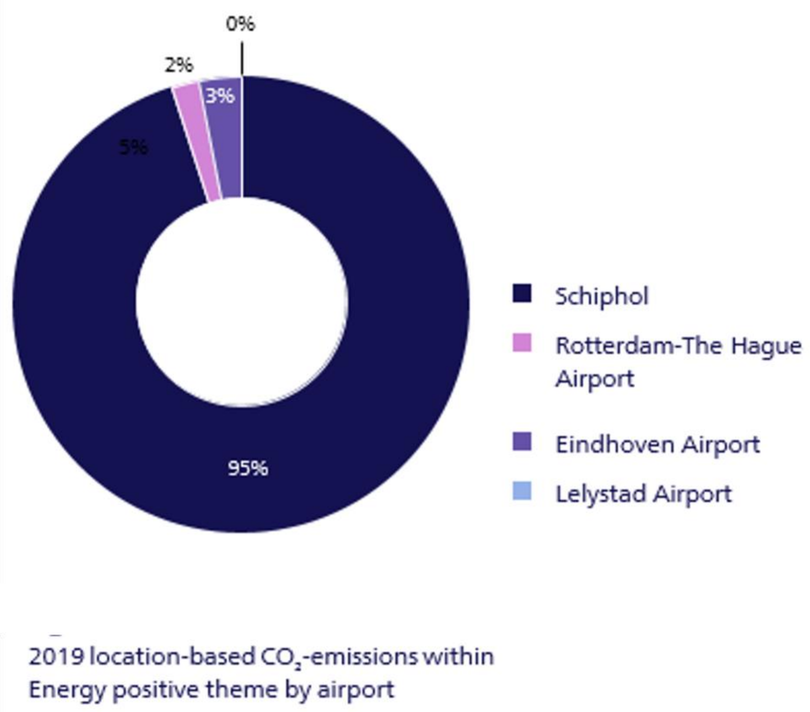


Figure 10 Schiphol emissions Energy Positive share in % per airport

Zero-emissions airports Schiphol Group's four Dutch airports are on track to become zero emissions airports by 2030. This means, for example, that we aim to phase out natural gas in all our offices and buildings by 2030. We have been implementing our roadmap since 2020 to achieve this goal. To give our internal target a boost, we have committed to the goals of the Dutch Green Building Council and aim to align our commercial buildings with the Paris climate commitments by 2030. Schiphol Group endorses the national, European and international climate agreements. We are committed to reaching the targets set out in the Paris climate agreement, which are translated into the 2019 Klimaatakkoord ('Dutch Climate Agreement') and the set of measures of Fit for 55 presented by the European Commission. We expect to achieve a 90% reduction in our natural gas consumption, which is mainly for heating and cooling our buildings, by 2030 compared with 2019. On a few cold days each year, peak heating with green gas may still be required by 2030. As far as we are not entirely independent from natural gas by then, any consumption will be in the form of green gas. As a transitional solution, we intend to purchase all our natural gas as green gas by 2030 at the latest. Since 2019, we purchase 100% green gas for Eindhoven Airport and Rotterdam The Hague Airport, for Schiphol Airport be buy approx. 10% green gas. Biogas is generated from renewable sources and subsequently upgraded to the quality level of natural gas. Vertogas green gas certificates are awarded to Schiphol Group on a yearly basis, and the contract with our supplier runs until 2024. Schiphol Group buildings fall under two main categories: new buildings and renovations.

Below an overview of the current footprint of Schiphol (location Amsterdam Airport) is provided for the year 2022 compared to 2021.

CO_2e emissions at Amsterdam Airport Schiphol[1]

(in tonnes)

in tonnes	2022 Location-based	2022 Market-based	2021 Location-based	2021 Market-based
Scope 1 - Within TPI[2]	17,728[3]	16,331[4]	20,796[3]	18,256[4]
Refrigerants and de-icing	N/A	N/A	476	476
Scope 2[5]	87,125[6]	0	76,350[6]	0
Total Scope 1 and 2 CO_2e emissions	**104,853**	**16,331**	**97,622**	**18,732**
Scope 3 - Airside fuel used by third parties, own staff commuter traffic & business trips by air/own car	34,680	34,680	19,451	19,451
Total CO_2e included in Sustainability TPI for Amsterdam Airport Schiphol	**139,533**	**51,010**	**116,596**	**37,707**
Scope 3 - Kerosene for outbound flights and other items[7]	N/A	N/A	8,906,955	8,902,603
Total Scope 3[8]	**N/A**	**N/A**	**8,926,406**	**8,922,054**
Total CO_2e footprint			**9,024,027**	**8,940,786**

1 CO_2e emissions are likely to reflect 1/3 of the climate impact of aviation. The non-CO_2 emissions are not quantified yet, because further reflection on how to best address non-CO_2 climate impacts is required.
2 Consists of the categories: gas under the Schiphol Nederland BV licence, fuels used by own vehicle fleet, fire brigade, emergency power and own staff business trips by lease cars. From 2022 onwards, CO2 emissions from gas do not include a correction for standard weather conditions ('graaddagencorrectie').
3 Grey gas emission factors have been applied for location based purposes.
4 Since 2019, Amsterdam Airport Schiphol has been purchasing green gas for part of its consumption.
5 Consists of electricity consumption by Amsterdam Airport Schiphol.
6 Grey electricity factors have been applied for location based purposes.
7 Other Scope 3 items are not part of the Sustainability TPI definition and include, among others: electricity and gas consumption by third parties, all road traffic to and from the airport and fuels related to aircraft handling and landing and take-off cycle. 2022 data will be reported with a one year delay.
8 Total scope 3 data is reported with a one year delay.

Figure 11 Overview of CO2e emissions at Amsterdam Airport Schiphol

The sustainability TPI target was met in 2022, mainly due to lower gas consumption. To show our commitment, going forward we will specify the energy needs of our commercial real estate at Schiphol and our Scope 3 (value chain) emissions in our annual report. We will also continue with our renovation plans for our buildings and intensify our collaboration with our handlers to phase out fossil fuels at airside.

In 2022, the ATES installation in the WTC 1 office building was our biggest contributor to lowering gas consumption. Once this installation reaches its optimal functioning capacity, gas use will be phased out in this building. Because the ATES is functioning as planned, the backup gas installation for Terminal 3 will be removed in 2023. In addition, the optimisation of the new ATES also means we needed less energy for the heat pumps.

Figure 12 Progress CO2e target Energy Positive

Based on our performance to date, we are well on our way to realising our 2030 targets. Looking forward, we are aware that there is still much to do. Our results to date and our ongoing efforts underline a high sense of urgency and awareness of the need to achieve our sustainability goals. Our current emissions from natural gas and other fossil fuels (Scope 1 and 2 plus commuter traffic and business trips of own employees in Scope 3) have been offset by Gold Standard and VCS projects since 2012. We regard offsets as an interim solution, and our zero-emission 2030 goal does not include any offsets. Our expected emissions reduction of over 90% by 2030 exceeds the national targets of the Dutch Climate Act and the latest IPCC recommendations.

Commercial buildings

Ten commercial buildings at Schiphol have a BREEAM certificate, which amounts to 20% of our commercial building portfolio.

BREEAM is a rating system for sustainable buildings. The Base A, The Base D and the morgue received a BREEAM certificate in 2022.

Energy use commercial buildings

(x 1,000)	Size (m²)	Electricity (kWh)	Natural gas (m³)
Schiphol HQ (SHG)[1]	34	39	144
Commercial Real Estate[2]	594	34,462	2,905

1 Incl. datacenter
2 Excl. Rotterdam Airport Real Estate (RAV)

Figure 13 Overview Energy Consumption Commercial Buildings Royal Schiphol Group

New buildings

From 2025 onwards, all newly completed own buildings at Schiphol Airport, Rotterdam The Hague Airport and Lelystad Airport will be energy positive, with energy- efficient designs, aquifer renewable thermal energy storage (ATES) and solar power integrated as standard elements. International sustainable building certificates are used as a benchmark and framework during the design and construction of new buildings. We apply LEED certification (gold/platinum) for new terminal buildings and BREEAM certification (excellent/ outstanding) for new commercial properties.

Renovations

Existing own buildings will be upgraded to at least energy-neutral at natural renovation moments in their lifecycle. Phasing out gas during renovations is more challenging than developing new buildings without natural gas, since our airports are always in operation. Further difficulties are presented by maintenance planning and deprecation, and the early devaluation of assets. Some older buildings are less suitable for heating without natural gas, which occasionally makes it difficult to implement the newest energy conservation measures. Installing ATES is the preferred solution to reduce gas usage with similar electricity needs, being the main reason for the 40% reduction in natural gas emissions from our buildings since 2010. A key current project involves installing ATES in terminals 1 and 2, reducing our gas consumption by 35% compared with 2019.

All required renovations of our remaining buildings to phase out natural gas are scheduled for the upcoming years to achieve our 2030 target.

Renewable energy supports our carbon-reduction programmes. The electricity purchased by Schiphol Group comes mainly from wind – and to a lesser extent from solar – farms in the Netherlands, though the amount of solar is increasing. Green gas accounts for 14,46 % of total Group gas purchases and 100% of the gas used by Eindhoven Airport.

In 2022, solar panels at Schiphol Airport produced a total of 2.6 million kWh. Due to the many hours of sun in 2022, the yield of the existing PV panels was considerably higher than 15%. At Rotterdam The Hague Airport, we opened a new solar farm with more than 37,000 solar panels (7.7 hectares). The solar panels generate as much energy as 5,100 households.

Solar energy per airport

	Solar energy (mWh) generated on site in 2022
Schiphol Airport	2,595
Eindhoven Airport	205
Lelystad Airport	18
Rotterdam The Hague Airport	674
Unisun solar park at RTHA	205

Zero-emission mobility

Schiphol Group owns and leases a mixed fleet consisting of light and heavy vehicles (Scope 1), with all light vehicles set to be replaced by electric vehicles over the coming years. We are monitoring developments in the powertrain and clean fuels for heavy vehicles. For each potential replacement case, we balance the need for operational performance with environmental and safety concerns.

We take steps to stimulate clean commuting for Schiphol

Group employees (Scope 3). For example, all new lease cars offered to staff are electric and we also provide financial incentives to encourage people to commute by bike. Meanwhile, the COVID-19 pandemic has increased the number of digital meetings, reducing commuter traffic and business trips. Air travel by Schiphol Group for work is partly undertaken using sustainable aviation fuels; offsetting is used to compensate for the remaining emissions, in addition to offsetting emissions from commuter traffic (Scope 3).

Zero-emission airside

Schiphol Group is undertaking an ambitious programme to reduce airside emissions to zero by 2030 (Scopes 1 and 3). We aim for a reduction in fuel consumption of at least 90% by 2030, compared with 2019. This ambition relates to our own equipment, the required (energy) infrastructure and third-party equipment, among other elements. Some of our operational vehicles will be electric in the near future; where there is not a viable zero-emission alternative, we use 'transitional' clean fuels such as HVO100. Currently,HVO100) is the standard fuel used at Schiphol airside. HVO100 is better than diesel for local air quality and has been the default fuel at airside since 2023.

As well as reducing CO2 emissions, we prioritise airside projects that will minimise other climate forcers such as nitrogen oxides (NOx). We also aim to improve local air

quality by reducing concentrations of fine particles and ultrafine particles (UFPs) and substances of very high concern (SVHC). To do so we approached our airside stakeholders and produced a collaborative roadmap in which we made an overview of all vehicles on airside and inventoried whether zero emission alternatives are available and on how to phase them out for zero-emission ones.

Equipment

We do not expect to replace our existing snow fleet equipment and fire brigade equipment with zero- emission vehicles by 2030. Instead, these engines will be powered by HVO100. We are still considering zero- emission alternatives for propane, a gas used in firefighting simulations and training practices.

Meanwhile, we continue to monitor the development of zero-emission firefighting equipment that adheres to the highest operational and safety standards. When such solutions become available, Schiphol Group will transition our remaining fleet at a natural moment in its lifecycle. Collaborating with many stakeholders, Schiphol Group aims to be a catalyst for change in our industry as we strive to reach our wider sustainability and carbon-emission objectives (Scope 3). The installation of electric charging facilities at airside will be key in speeding up the transition to clean mobility at our airports, as will the support we offer our partners to transition from fossil fuels to renewable energy sources (Scope 3). Stationary aircraft normally use their own kerosene-driven auxiliary motors (APU) or a separate diesel-powered generator (GPU) to supply electricity and air conditioning. To reduce this form of fossil fuel use (Scope 3), we have equipped the majority of aircraft stands with installations for fixed electrical ground power (FPU) and electric pre-conditioned air units (E-PCAs). Currently, our G-pier is already fully equipped with E-PCAs and this number will rise as Schiphol ordered 25 new E-PCAs in 2023. The availability of FPUs, E-GPUs and E-PCAs will be expanded to all connected aircraft stands at Schiphol Handlers own the ground-support equipment used at our airports, and replacing zero-emission equipment depends on their specific replacement calendars.

Together with a supplier, we have co-developed an electric ground power unit (e-GPU) that supplies zero- emission power to aircraft docking at remote aircraft stands as an alternative to traditional diesel GPUs. With handlers and airlines, we are working on the implementation of the e-GPUs in the procedures. At Rotterdam The Hague Airport, all GPUs will be zero- emission by 2026, and all ground-support equipment will be zero-emission by 2027. Airport regulations to enforce this are currently being drafted. At Eindhoven Airport, over 65% of GSE is already zero-emission.

Renewable energy

Since 2018, all Schiphol Group airports in the Netherlands have been powered by newly built Dutch wind farms located both onshore and offshore. We have a long-term purchasing contract (2018-2032) in place with our electricity supplier, Eneco. This PPA-contract includes Guarantees of Origin (GoO) certificates for all electricity used by our own operations, as well as all ground operations at airside and all buildings leased by Schiphol Group to third parties.

Our next step will be to generate more renewable energy on site at our airports. Given the difficulty of generating geothermal energy or locating wind farms near runways, we consider solar energy to be the most practical and clean energy option for an airport. Schiphol Airport and Eindhoven Airport are developing plans for on-site solar farms. At Rotterdam The Hague Airport, 100% of available roofs are already covered with solar panels and the airport opened a 14 MWp solar park in spring 2022. This key installation generates approximately three times the annual electricity consumption of the airport, which means surplus electricity is supplied to the local grid. Several of our solar power installations will be replaced with the latest- generation technology in the near future.

The recently opened solar park at Rotterdam The Hague airport is a major step towards our goal of generating 21 MWp locally at our four Dutch airport locations by

2030 and to generate all energy needed on our airport premises by 2050.

We expect increased demand for electricity at our airports over the coming decade, driven by the shift from fossil fuels. Schiphol airport owns and operates its own energy grids, and these must be strengthened to provide sufficient capacity for this energy transition. The grid at Eindhoven Airport faces a similar challenge as well.

Third party buildings

Several third parties, including KLM and LVNL, own buildings on the airport sites and arrange their own energy contracts (Scope 3). For these locations, our targets are aligned with the Dutch Climate agreement. We aim for net-zero-carbon-emissions from built environment at our airport locations by 2050. The Dutch Climate Act provides guidance on the required reductions towards 2050. We consult with the owners of these buildings to learn more about their plans to decarbonise including their plans to install solar panels. Such changes influence electricity demand and supply, which must be factored into grid development. During the coming years, we will discuss opportunities for acceleration and mutually beneficial solutions; for example, aligning investment in new ATES. Buildings owned by third parties fall outside the scope of our 2030 zero-emissions target.

GRID developments

We are monitoring technological developments in terms of grid balancing as well as smart-energy storage facilities such as batteries. Eindhoven Airport is an active participant in the development of a local energy trading platform. Companies at the airport and nearby business parks can trade the energy they generate themselves among themselves without involving energy suppliers. Among its many benefits, this project is an important first step towards preventing grid overload.

The Energy Management System (EnMS) of RSG

The scope of the EnMS covers, the design, construction, procurement and maintenance of all energy using facilities, installations, equipment and systems.[11]. An illustration of the overall governance of the EnMS (in Dutch) according to the “High Level Structure” of the ISO (International Standard Organization) is provide below.

[11] Also see “NEN-EN-ISO 50001 Energiemanagementsystemen - Eisen met gebruiksrichtlijnen”.

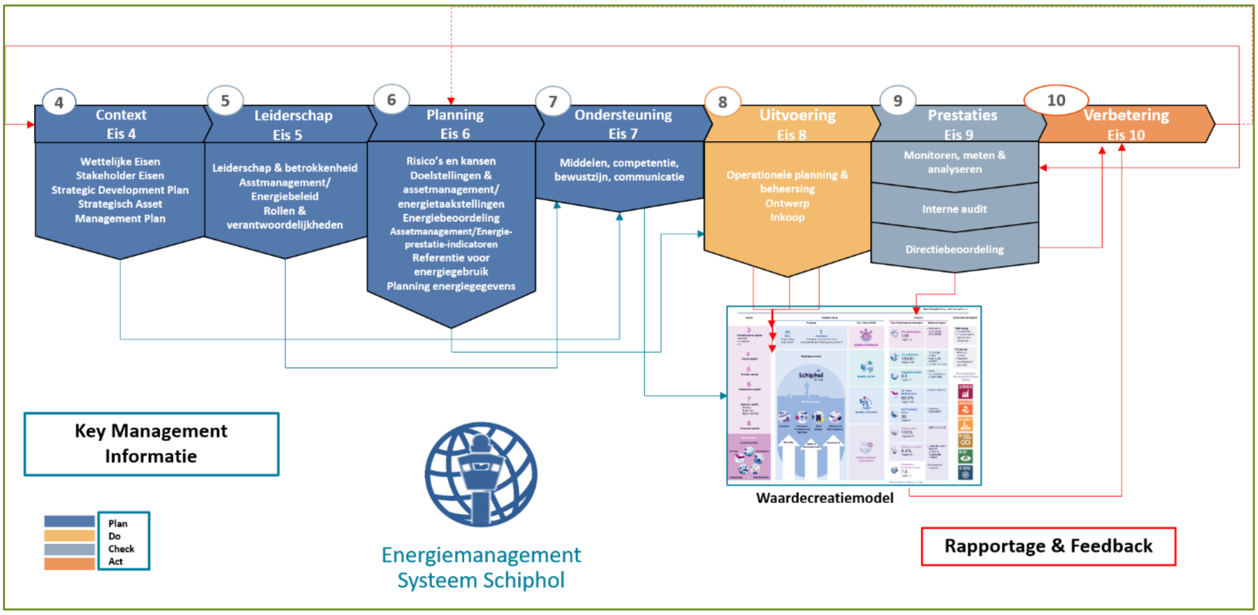


Figure 14 Depiction of the governance of the Energy Management System of the RSG

The EnMS of the RSG consists of:

1. An Energy Policy;
2. Energy targets (including Energy Performance Indicators);
3. Energy responsibilities (activities that employees perform for the EnMS);
4. Plans for the improvement of the energy-efficiency, the energy consumption and final energy usage and plans to remain compliant to the applicable energy legislation and other (policy) requirements.

The EnMS of the RSG ensures that we meet our targets and our energy responsibilities. Mitigation and corrective measures are taken, when necessary, to ensure we continually improve our EnMS. Energy performance encompasses, energy-efficiency, energy consumption and final energy usage. Which is applicable for sustainable energy generation (location based and market based). Energy Performance Indicators (EnPI's) and Energy baselines (EnB's) have been determined (chapter 6 of the EnMS handbook gives a detailed description). The EnPI's and EnB's enables RSG to show the improvement of our energy performance. Annually an Energy review is devised that describes the Significant Energy Usage (SEU), energy conservation measures (ECM), energy-efficiency improvement measures and renewable energy projects that can be executed. The EnMS is externally and internally audited annually.

8.1.3.1 Plan-Do-Check-Act-cycle (PDCA)

The EnMS of RGS is based on the Plan-Do-Check-Act-system (PDCA) for continuous improvement. This means that the EnMS is integrated in the operational processes of RGS. The most important processes are asset management processes.

PDCA-cycle of RSG is set-up in accordance with the requirements of the ISO 50001:

- Plan: gather insights into the context of RSG, determine energy policy, and set up of energy management organization, devise actions and determine risk and opportunities for improvement, execute an energy review, identify SEU's and EnPI's, determine EnB's, set energy targets and energy tasks and responsibilities, devise plans to achieve set goals and targets in line with the energy policy.
- Do: implement the (energy)plans, execute operational and maintenance measures, implement communication plans, incorporate energy requirements during procurement and contracting and execution of building and construction. Assure the required skills and competences are imbedded in the organization.
- Check: energy performance and monitoring, measuring, analysing, evaluating, auditing of the EnMS and performing management reviews of the EnMS.
- Act: taking preventive, mitigation and corrective measures to ensure that energy performance and the EnMS is continuously improved.[12]

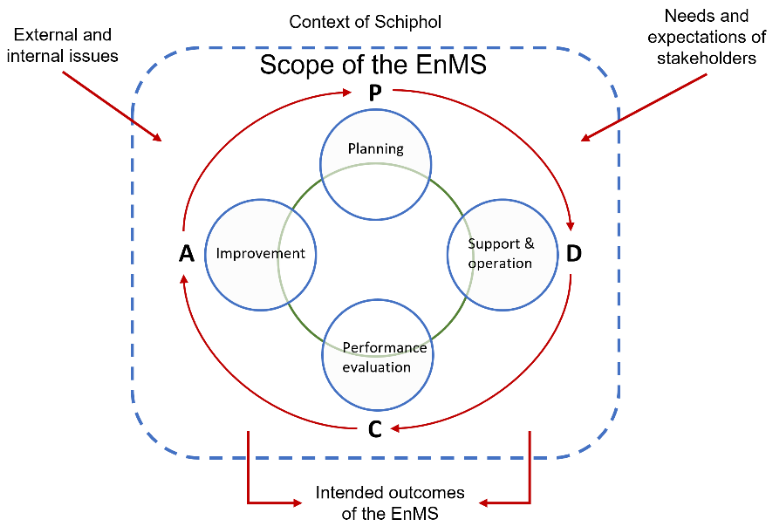


Figure 15 PDCA of the EnMS (ISO 50001)

8.1.3.2 Introduction to the airport energy grid

Description of final energy demand

Below Figure 8-17 depicts the final energy demand of RSG. The majority of the final energy demand comes from the terminal and piers of which the main demand is for heating and cooling.

[12] Also see "NEN-EN-ISO 50001 Energiemanagementsystemen - Eisen met gebruiksrichtlijnen".

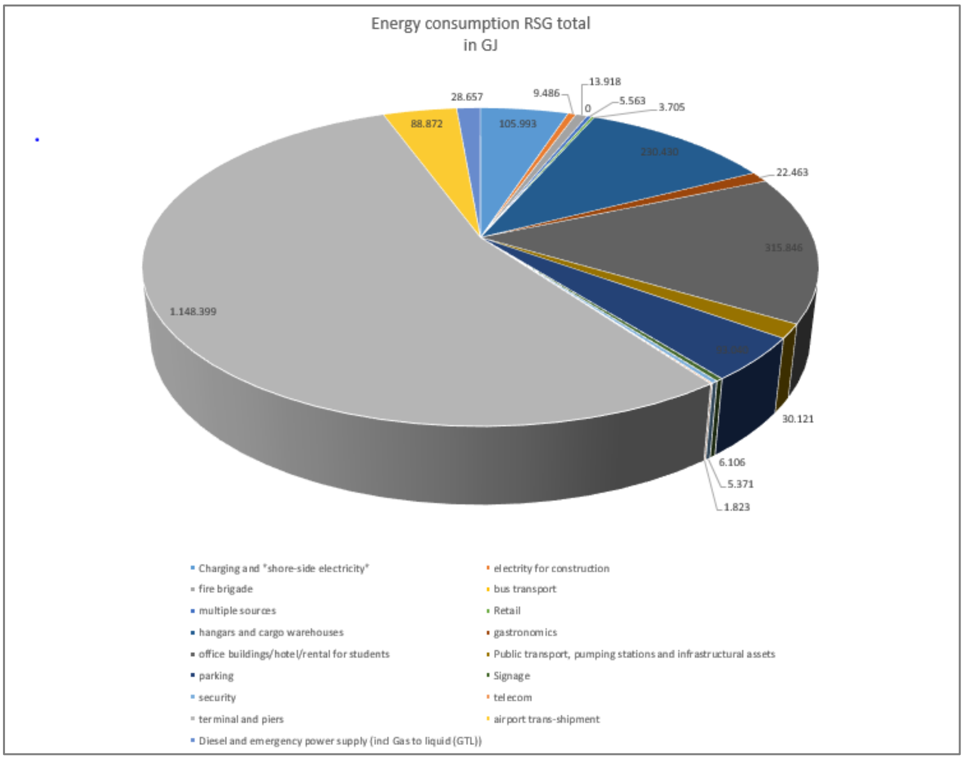


Figure 16 Division of final energy demand of RSG (in GJ)

Table 2 Final energy demand by process at RSG (2022)

Energy (electricity, natural gas, diesel and emergency power supply)							
Proces	Total Energy Amsterdam Airport Schiphol 2022 (GJ)	Total energy Rotterdam the Hague Airport 2022 in GJ	Totaal energie Rotterdam Real Estate 2022 (GJ)	Totaal energie Eindhoven Airport 2022 in GJ	Totaal energie Lelystad Airport 2022 in GJ	Total energy Schiphol Group Netherlands 2022 in GJ	in %
Charging and "shore-side electricity"	105756	237				105.993	5%
electrity for construction	9486					9.486	0%
fire brigade	11251	2.127			540	13.918	1%
bus transport	0					0	0%
multiple sources	4771	32		749	11	5.563	0%
Retail	0			3.705		3.705	0%
hangars and cargo warehouses	222285	3.811		4.334		230.430	11%
gastronomics	10089			12.374		22.463	1%
office buildings/hotel/rental for students	265723	4.573	26.367	13.116	6.067	315.846	15%
Public transport, pumping stations and infrastructural assets	29254	867				30.121	1%
parking	85715	158		7.167		93.040	4%
Signage	6106					6.106	0%
security	5241			6	124	5.371	0%
telecom	1330			493		1.823	0%
terminal and piers	1092479	18.478		34.012	3.430	1.148.399	54%
airport trans-shipment	80105	8.377		390		88.872	4%
Diesel and emergency power supply (incl Gas to liquid (GTL))	11.600	5.774	0	10.841	442	28.657	1%
Propane	4.078						
Petrol	2.344						
Green electricity	2.954						
Kerosine	5.140						
Total	1.955.707	44.434	26.367	87.187	10.614	2.109.793	100%

Tabel 8-6 below provides the energy consumption per building for Amsterdam Airport Schiphol for the buildings that are in scope of the department Schiphol Infrastructure. These buildings are non-commercial buildings. Table 8-7 provides an overview of the buildings at Amsterdam Airport Schiphol that are commercial buildings. Generally, these buildings, have either single tenants or multi tenants that lease the building for a certain period. At Amsterdam Airport Schiphol, in scope of the EnMS, the remaining energy consumption is electricity for airside operations, electricity for public transport and electricity for parking[13].

Table 3 Energy consumption per building Amsterdam Airport Schiphol (scope of Schiphol Infrastructure)

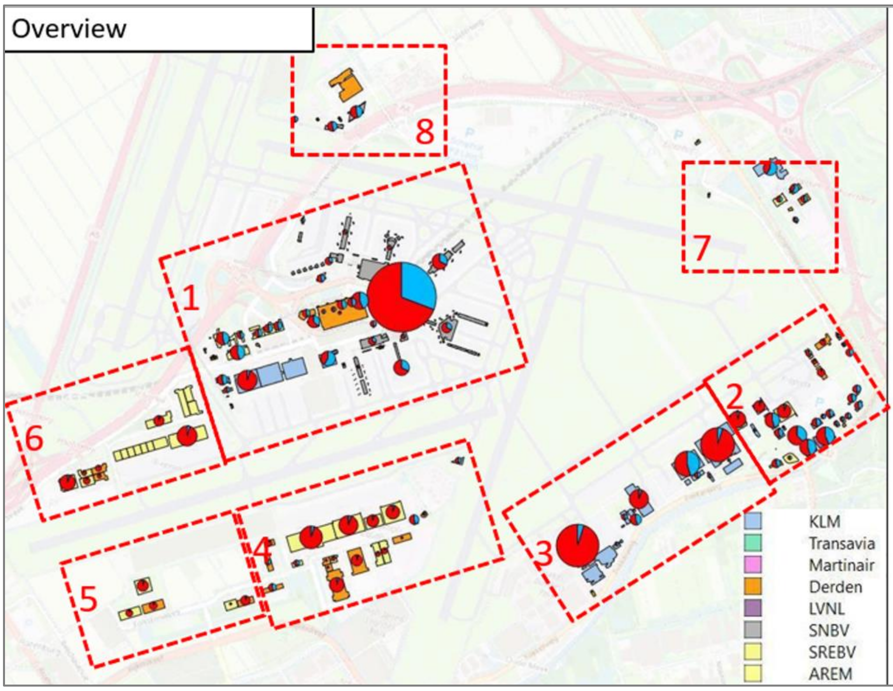
Pier	Elektriciteit in kWh	gas in Nm3	gas in kWh	totaal energy consumption E+G (kWh)	CO2 in tonnen	label	m2	kWh'/m2 electricity & gas
B-pier	3.673.677	90.303	882.167	4.555.844	1.620	A++	17804	255,9
BC -corridor	424.584	0	0	424.584	169	D	5405	78,6
C-pier	2.618.403	302.185	2.952.041	5.570.444	1.580	C	13605	409,4
D-pier	9.408.783	75.580	738.337	10.147.120	3.870	A	90791	111,8
E-pier	7.611.126	239.727	2.341.890	9.953.016	3.450	A+	97144	102,5
F-pier	2.987.986	22.395	218.775	3.206.762	1.226	A	28447	112,7
G-pier	4.024.813	43.770	427.585	4.452.398	1.676	A+	36765	121,1
H-pier	1.221.097	77.518	757.269	1.978.366	623	A++	10861	182,2
GH gebouw	825.679	0	0	825.679	328		5613	147,1
BMC	1.411.193	0	0	1.411.193	560	A	16073	87,8
Skyport	806.383	0	0	806.383	320	G	4547	177,3
Plaza	2.806.751	0	0	2.806.751	1.114	E	29584	94,9
Terminal 1	20.525.028	0	0	20.525.028	8.148	A	108282	189,6
Terminal 2	7.057.586	3.549.658	34.676.609	41.734.195	9.149	C	82356	506,8
Terminal 3	31.562.172	0	0	31.562.172	12.530	A	135359	233,2
Schoonmakersgebouw	167.967	32.575	318.225	486.192	125	E	1091	445,6
OND (Sneeuwvlootgebouw)	689.223	98.475	962.002	1.651.225	450	C	10890	151,6
Kantorendriehoek Post Sloten	48.725	7.111	69.467	118.192	32	C	804	147,0
Post Sloten	394.365	90.232	881.476	1.275.841	318	A	7535	169,3
Post Rijk	110.394	19.257	188.123	298.516	78	A	2370	126,0
Post Vijfhuizen	249.975	31.020	303.034	553.010	155	A	4442	124,5
Total	98.625.910	4.679.804	45.717.002	144.342.912	47.522		709.768	

[13] The electricity connections for airside operations, public transport and parking are not provided in this report due to the extensive amount of these connections. Furthermore the energy consumption per building for Rotterdam the Hague Airport, Rotterdam real estate, Lelystad Airport and Eindhoven Airport are excluded. The energy consumption is included in the overall energy consumption data.

Table 4 Energy consumption per building Amsterdam Airport Schiphol (scope Schiphol Commercial buildings)

Building		Elektriciteit in kWh	gas in Nm3	gas in kWh	total kWh consumption electricity & gas	CO_2 in tonnen	Energy label	aantal BVO	kWh/m2 electricity & gas
Columbus	Offices	529820	50345	491.825	1.021.644	300	A	7155	142,79
Folkstoneweg 67	Cargo	1045906	48169	470.560	1.516.465	501	D	5841	259,62
Ganderweg 1 en 1a	Cargo	283.229	61985	605.531	888.760	223	C	4893	181,64
Prestwickweg 2-8	Cargo	72801	8.259	80.687	153.488	44	B	2828	54,27
Reykjavikweg 2	Cargo	660404	40966	400.200	1.060.604	335	A	10037	105,67
Vrachtstation 10	Cargo	1217401	28937	282.681	1.500.082	535	A	12604	119,02
Vrachtstation 11	Cargo	1598914	122212	1.193.890	2.792.804	853	A	23580	118,44
Vrachtstation 19	Cargo	650738	42862	418.716	1.069.454	335	A	10654	100,38
Vrachtstation 8	Cargo	2.675.351	351.237	3.431.234	6.106.585	1.690	A	46054	132,60
Vracht 9	Cargo	2.418.979	35802	349.749	2.768.728	1.024	A	32347	85,59
Caravelle	Cargo	608134	162668	1.589.102	2.197.236	532	C	5738	382,93
Constellation	Cargo	369.069	35801	349.738	718.807	211	A+	6747	106,54
GA Terminal	Terminal	593088	26303	256.955	850.043	282	A++	6559	129,60
Gebouw 144	Offices	119.478	32546	317.945	437.423	106	G	4107	106,51
Avioport	Offices	1.202.620	8979	87.711	1.290.331	493	A+	14283	90,34
SHG	Offices	4677510	51325	501.394	5.178.904	1.949	A	33617	154,06
TheBase totaal incl. TheBaseD (ATES and heat pump shared)	Offices	3.427.449	55.180	539.053	3.966.502	1.459	A+++	64033	61,94
Outlook1	Offices	2439743	88045	860.114	3.299.857	1.126	A+	38826	84,99
Outlook 2	Offices	3077754	168276	1.643.887	4.721.641	1.523	A+	25195	187,40
Mortuarium	Offices	47299	0	0	47.299	19	A++	525	90,09
WTC1	Offices	3558859	38900	380.014	3.938.873	1.482	A+	25586	153,95
WTC2	Offices	2284573	74864	731.346	3.015.919	1.041	A++	31224	96,59
AFC	Cargo	218078	25279	246.947	465.024	132	C	6876	67,63
Freightway	Cargo	753001	155854	1.522.533	2.275.534	578	C	16070	141,60
Uiverweg	Cargo	1028964	70733	690.986	1.719.950	535	B	13197	130,33
Valkweg 1	Cargo	292643	33978	331.929	624.572	177	B	6386	97,80
Vracht 5	Cargo	2170570	137483	1.343.071	3.513.641	1.108	C	29900	117,51
Vracht 6	Cargo	1886671	261798	2.557.505	4.444.176	1.217	D	29989	148,19
Northport	Cargo	198321	38965	380.649	578.970	148	A	6083	95,18
Tristar C	Offices	820011	7065	69.013	889.024	338	A++	5299	167,77
Tristar B	Offices	399015	10356	101.169	500.184	177	A++	4991	100,22
Tristar A	Offices	309649	10957	107.042	416.691	143	A++	4991	83,49
Transport	Offices	1186048	23493	229.507	1.415.555	513	A+++	12986	109,01
Total		42822087	2309621	22562685	65384773	21130		549201	

Figure 8-17 below shows the heating and cooling demand per cluster of buildings at Amsterdam Airport Schiphol. This data was taken into account for the modelling scenario's.



Cluster	#	Gas Consumption	Heating demand	Cooling demand
Centre	1	44%	42%	53%
East North	2	14%	15%	21%
East South	3	21%	22%	12%
South-east North	4	10%	11%	4%
South-east South	5	1%	1%	0%
South	6	4%	5%	1%
North	7	4%	2%	6%

Figure 17 Depiction of Heating and cooling demand at Amsterdam Airport Schiphol (Schiphol Group and third parties)

Conversion of Combined Heat and Power (CHP) installation at Amsterdam Airport Schiphol. Currently there is one remaining CHP in Terminal 2. The CHP will be taken out of operation in 2027. The CHP has an electric efficiency of 35% and a thermal efficiency of 52%. When the CHP is taken out of operation it will be replaced by an Aquifer Thermal Energy-storage System with heat pumps (also see description below). The current climate system is under revision to facilitate a low temperature regime.

The co-efficiency of performance for the heating installations of the remaining boilers on average equals 94%. The HR boilers on average have co-efficiency of performance of 100 – 107%. Phasing out of all natural gas is part of the goals of the Sustainability Roadmap before 2030.

For RSG several technologies are available to phase out gas for Schiphol Centre:

- **District heating** uses excess warm water from for example industry. Heat then to be transferred to cold for cooling. Requires heat source nearby – currently not a viable option at Schiphol Centre. Feasibility of district heating in other areas need to be examined in relation to third parties
- **Geothermal source** uses warm water in deep earth layers to heat up water. Requires expensive, deep drilling and currently not considered an option
- **ATES** (Aquifer Thermal Energy Storage) and heat pumps use a water layer at ~150-200m depth to store hot water in summer to be used next winter and cool water in winter to be used next summer. Same principle applies for both heating and cooling – energy efficiency of both heating and cooling is increased. ATES thus shifts gas to electricity and lowers the total energy use.

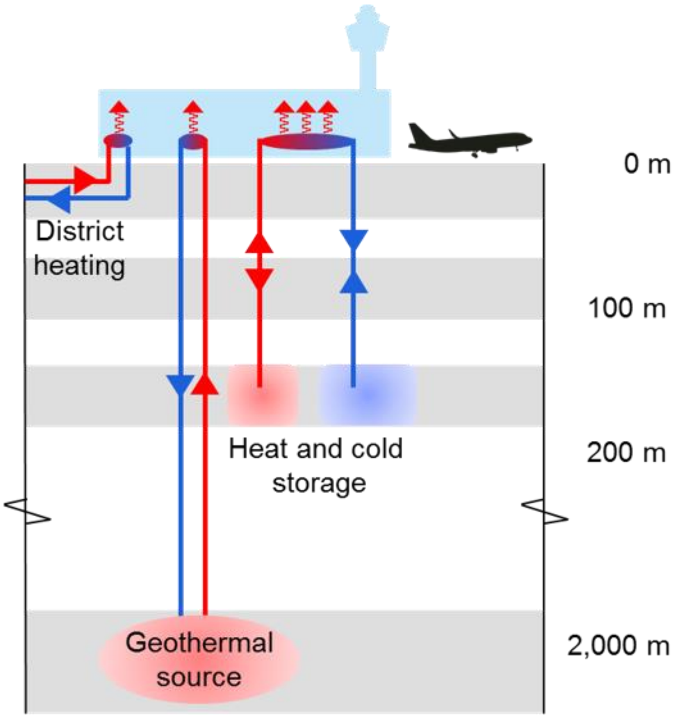


Figure 18 Illustration of techniques to phase out natural gas

Figure 8-19 below shows the ATES's for Amsterdam Airport Schiphol Centre.

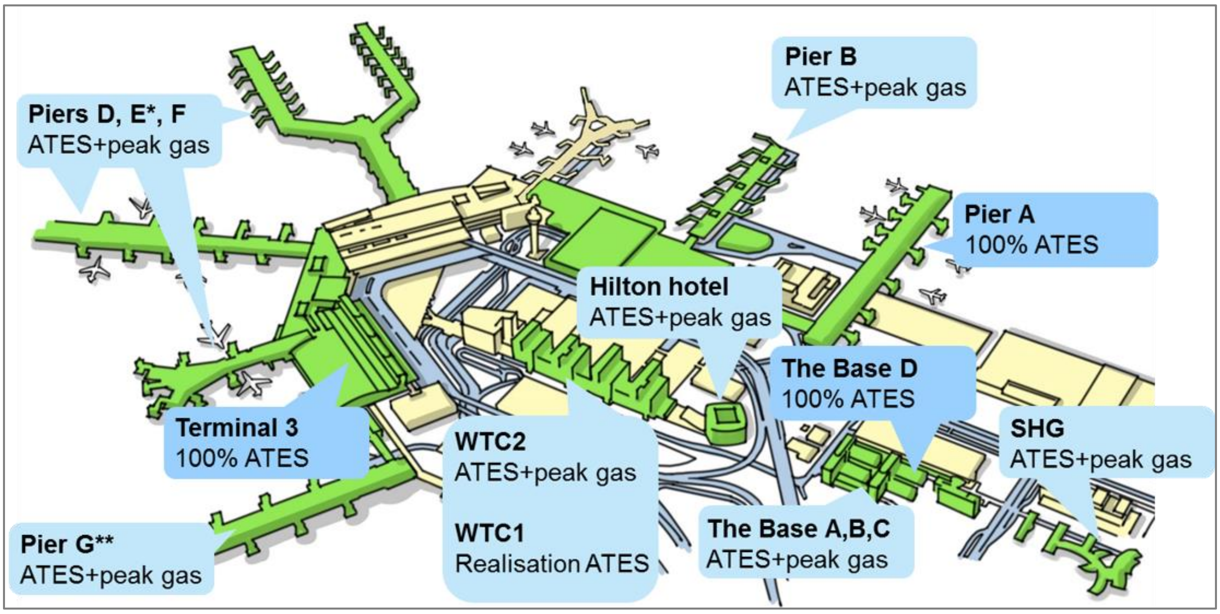


Figure 19 Illustration of ATES at Amsterdam Airport Schiphol Centre.

* Pier E has partial ATES only (investment decision, second part postponed in project Take-off).
** Pier G has 100% ATES installed, but a few local high-temperature systems have not yet been phased out. *Source: 'Bijdrage WKO aan verduurzaming Schiphol'*

8.2 Introduction to Torino airport

8.2.1 General introduction of Torino airport

Torino Airport is located in Piedmont, in the heart of North-West of Italy, one of the most important economic and business centers in Italy and Europe. Torino is the 4th most important city in Italy and hosts several cultural and historical attractions.

Torino Airport is located 15 kilometers from Torino downtown. The city center is easily accessible via dedicated highway and railway station.

Figure 8-20 – Location of Torino Airport in the homonymous city of Torino, in North-West Italy.

For what concerns meteorological data, the climate is predominantly continental with cold winters and warm but fairly wet summers. Below (Table 5) can be found an average of the last five years concerning maximum, minimum and average temperatures and heating and cooling degree days. Heating degree days are referred to 26 °C, while cooling degree days are referred to 18 °C to have a better representation of the variation of temperatures during summer.

Table 5 – Climatic characteristics of the region of Torino Airport (five-year average). DD: Degree Days.

	T max [°C]	T Min [°C]	T Average [°C]	DD heating	DD cooling
Jan	15.2	-5.2	2.9	529	0
Feb	19.6	-4.7	5.6	406	1
Mar	21.6	-2.3	8.5	359	2
Apr	25.3	0.4	13.0	158	15
May	27.1	5.2	17.0	27	46
Jun	33.6	12.3	22.4	0	145
Jul	34.3	11.1	24.6	0	208
Aug	33.9	10.4	23.9	0	186
Sep	30.2	7.7	19.7	0	84
Oct	24.3	5.7	14.2	90	12
Nov	17.1	-1.2	8.1	358	0
Dec	14.4	-4.8	3.5	512	0
			Total	**2439**	**698**

SAGAT is the company that has been responsible for the management and development of Torino Airport since 1956. The company's concession is valid until 2037, with the founded possibility of an extension until 2055.

SAGAT SpA is a private company, controlled by F2i, an asset management company established in 2007. F2i is an Italian leading closed-end fund among the largest in Europe with assets under management of about 5 billion Euros invested in key sectors.

The Category 4E runway has a TORA of 3,300 meters and a capacity of 28 movements per hour.

Figure 8-21 - View of category 4E runway at Torino Airport.

The aprons can accommodate up to 31 commercial and 9 general aviation aircraft; 6 aprons are served by boarding bridges.

The Passenger Terminal covers an area of over 54,000 square meters. The structure, arranged on 3 main levels, is characterized by a large panoramic window that from the boarding halls overlooks the aircraft movement areas. The infrastructure is equipped with 48 check-in stations and 22 gates. The various floors, integrated with each other and free of architectural barriers, favor passengers with reduced mobility who can use dedicated services on request. Spacious waiting areas, a large shopping arcade (6,600 sqm) and lounges guarantee high service levels. The BHS system is capable of handling 3,600 bags per hour.

From 2003 to 2012, Torino Airport underwent a series of major investments that characterize its current infrastructural configuration. The Passenger Terminal was modernized and expanded for the 2006 Winter Olympics. For this occasion, the new BHS system, the General Aviation terminal as well as extensions to the aircraft parking aprons, bus and car parks were realized. In addition, a three-year plan for the general upgrading of the aircraft maneuvering areas was completed in 2012.

Below some of the main infrastructure features are highlighted:

- ✓ Capacity up to 8 million passengers/year (vs current 4 million) and 28 movements/hour
- ✓ Runway length: 3,300 meters
- ✓ Main terminal area 54,000 sqm
- ✓ Remote check-in Terminal
- ✓ General Aviation Terminal area: 4,700 sqm
- ✓ Cargo Terminal

The Cargo Terminal is present but is not the core business of the airport, thus not influencing the consumption in a strong manner.

Speaking about traffic, as for the entire sector, the years 2020 and 2021 were strongly affected by the Covid-19 pandemic, as visible in Figure 22. In winter 2021, starting in November, Torino Airport became a Ryanair base, with two aircraft based and the opening of 19 new routes, including 17 international ones.

Torino Airport registered its traffic record in 2022, with 4,193,881 passengers choosing the airport for their trips, breaking the previous record of 2017 (4,176,556 passengers) despite the early months of 2022 were still negatively impacted by the Omicron variant of Covid-19.

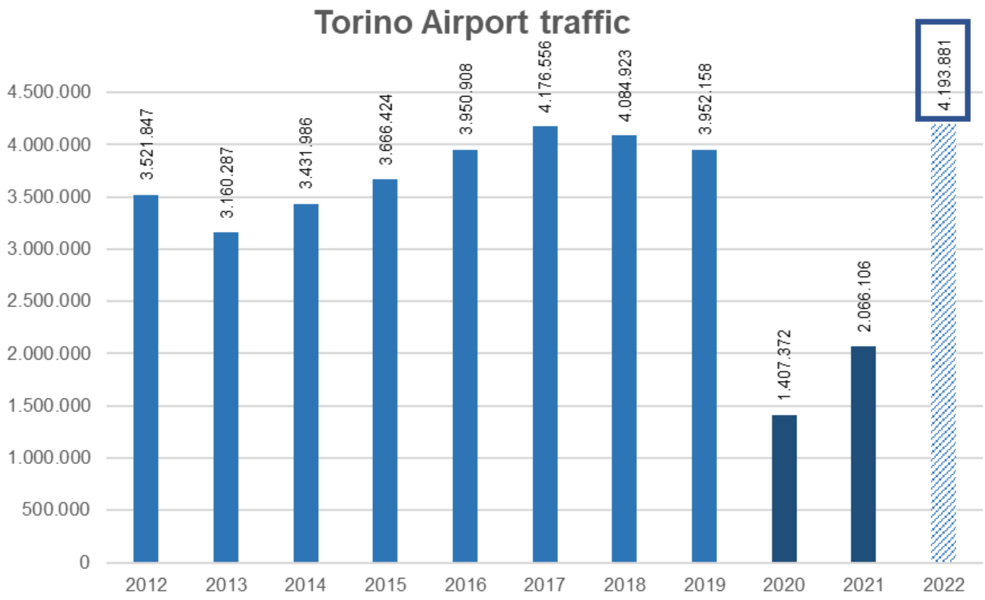


Figure 22 – Passenger traffic at Torino Airport from 2012 to 2022.

8.2.2 Airport climate footprint and ambitions

Torino Airport has completed its transition to Level 3 (Optimisation) of the Airport Carbon Accreditation (ACA) environmental sustainability programme, promoted by Airports Council International (ACI). The certification is for airport management companies that intend to pursue carbon neutrality goals, reducing CO2 emissions under their direct control with energy efficiency programs and the use of energy from renewable sources. Level 3 “Optimisation” features a stakeholder involvement plan in the emission reduction process, which is extended to the various actors operating at the airport (airlines, handlers, sub-concessionaires, passengers, employees, partners and local entities).

The mapping of the emissions related to Scope 1, 2 and 3 has been performed following the guidelines provided by ACA program.

The activities included in data that hereby presented are related to the proper management and operation of the service and facilities at Torino Airport, and in particular:

- HVAC air conditioning system;
- Lighting (excluding AVL runway lights);
- Baggage handling and sorting system (BHS);
- General services.

In addition, scope 3 emissions are related to:

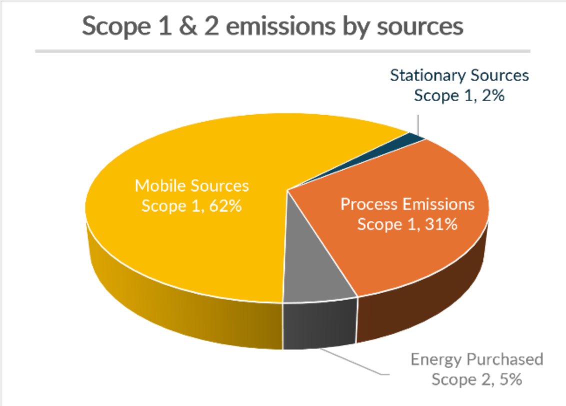
- HVAC air conditioning system of ENAV (national authority for flight assistance);
- Lighting related to AVL runway lights;
- GSE;
- LTO cycle including APU and Taxi consumption;
- Engine testing;
- Employees' home-work journeys;
- Employees' business trips.

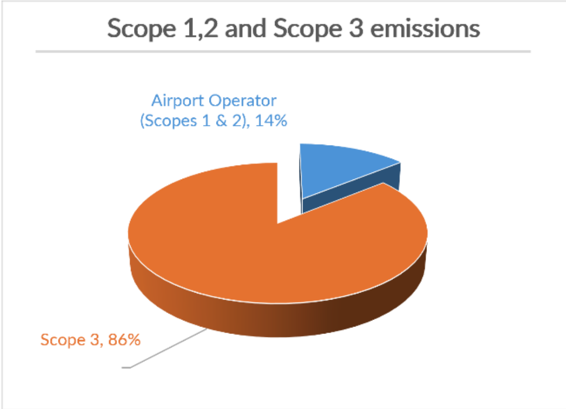
For the calculation of Scope 2 emissions, the ACA Scheme Guideline provides for the adoption of so-called dual-reporting, which consists of calculating CO2 emissions according to the following criteria:

- **LOCATION-BASED method** reflects the average electricity emissions of the country or region where the airport is located and uses an average emission factor specific to the grid on which the energy consumption occurs. Emissions are calculated by multiplying consumption by the emission factor of the national grid.
- **MARKET-BASED method** reflects the emissions from the electricity sources and products that have been purposefully chosen and, under strict conditions, allows for the use of an emission factor that is directly associated with the type of electricity purchased.

Market-based reflects the contractual choices of the party responsible for emissions, considering that the latter might choose one supplier over another also on the basis of the characteristics of the electricity supplied, in terms of emission factor.

The data reported below (Figure 23**Error! Reference source not found.**) follow the market-based methodology for 2022.





			Greenhouse Gases (tonnes)				
Source	**Entity**	**Group**	**CO2**	**CH4**	**N2O**	**CO2e**	**CO2e %**
Scope 1: Direct Emissions Airport Operator							
Vehicles (incl. airside transport machinery GSE)	Airport Operator	Mobile	126.7	0.005	0.007	128.6	0,36%
Buildings (gas/oil/coal)	Airport Operator	Stationary	1.647,4	0.160	0.005	1,653.1	4,60%
Emergency Generator	Airport Operator	Stationary	13.3	0.001	0.002	13.9	0,04%
De-icing/Glycol	Airport Operator	Process	250.3			250.3	0,70%
Refrigerants	Airport Operator	Process				1,9	0,01%
Subtotal	**Airport Scope 1**		2,037.7	0.2	0.0	2.047,8	5.69%
Scope 2: Airport Operator Net Energy from External Supplier							
Electricity purchased, Market-based EF	Airport Operator	Energy	.			-	0,00%
Subtotal	**Airport Scope 2**		-	-	.	.	0.00%
Airport Operator Sub-total (Scopes 1 & 2)						2.047,8	5,69%
Airport Operator Carbon Offsets			-			-	
Net Airport Operator Sub-total (Scopes 1+2, staff business travel, offsets)						2,064.6	
Scope 3: Emissions related to the Business Activities							
Aircraft LTO from 2 Detailed aircraft data (Best)	Tenant/3rd party	Aircraft	-			-	0.00%
Aircraft full flight (incl LTO)	Tenant/3rd party	Aircraft	31,326.8	-		31.326,8	87.11%
Aircraft APU	Tenant/3rd party	Aircraft	-	.		-	0.00%
Aircraft Engine Run-ups	Tenant/3rd party	Stationary	38.3	0.001		38.4	0.11%
Vehicles (incl. airside transport machinery GSE)	Tenant/3rd party	Mobile	598.6	0.000	0,001	598.8	1.67%
Buildings (gas/oil/coal)	Tenant/3rd party	Stationary	53.5	0,007	0,000	53.8	0.15%
Electricity purchased, Market-based EF	Tenant/3rd party	Energy	1.658,4			1,658.4	4.61%
Airport Operator Employee Commuting	Airport Operator	Landside	219.5	0.001	0.000	219.5	0.61%
Bus, shuttles	Public	Landside	0.1	0.000	0.000	0.1	0.00%
Airport Operator Staff Business Travel	Airport Operator	Business	16.8	0.000	0.000	16.8	0.05%
Subtotal	**Airport Scope 3**		33.912,0	0.0	0.0	33,912.6	94.31%
Total gross CO2e Airport Emissions (tonnes)						35.960	100%
Total net CO2e Airport Emissions (tonnes) [after any offsets]			35.950	0	0	35.960	

Figure 23 - Accounting of emissions from the various scopes at Torino Airport for the year 2022. Above, breakdown by source of Scope 1 and Scope 2 (left) and Scope 3 (right) emissions. Below, accounting tables with detailed information.

Torino Airport works to manage the airport infrastructure and operations in an energy-efficient way, avoiding the waste of resources and inspiring every action to respect the environment to the best of their ability.

Torino Airport joined the ACI Europe NetZero 2050 protocol in 2019 (zero emissions under the direct control of the airport) and in 2022 it signed the Toulouse Declaration (zero emissions related to the entire aviation sector), confirming its commitment to environmental sustainability in a long term scenario.

The intermediate target is instead related to the achievement of the objectives stated by the *Fit for 55* package that impacts not only on CO_2 emissions but also on primary energy demand and coverage of renewable energy systems on the total request.

The aim of the airport is by 2030 is to:

- reduce 39% primary energy supply,
- reach 40% RES production
- reduce 55% CO2 emissions (Scope 1 and 2)

Each of the targets is referred to 2010 as a baseline. Below the roadmap included in the Sustainability Report is shown (Figure 24).

Figure 24 - Torino Airport's roadmap to 2030 (excerpt from the Sustainability Report)

The scope of this analysis is to trace possible pathways in achieving these goals through the investigation of the existing solutions and looking for the optimum compromise in terms of speed and cost effectiveness of the mix. The analysis will focus on Scope 1 and 2, with some in depth studies on Scope 3 emissions that are inside airport boundaries, even if not directly under the control of management company.

8.2.3 Airport business scenarios

The business plan scenario considered is the Business Plan of the airport that sees a strong increase in the number of passengers in the short-medium term thanks to the recent introduction of the Ryan Air base in the Airport. This implies a doubling of the number of passengers in 2030 if compared to 2019 figures (seeFigure 25).

Inside the study a sensitivity analysis will be performed being the number of passengers a variable that affects the consumptions. In particular, the low and high scenarios foreseen by the Italian civil aviation authority (ENAC) will be taken into consideration.

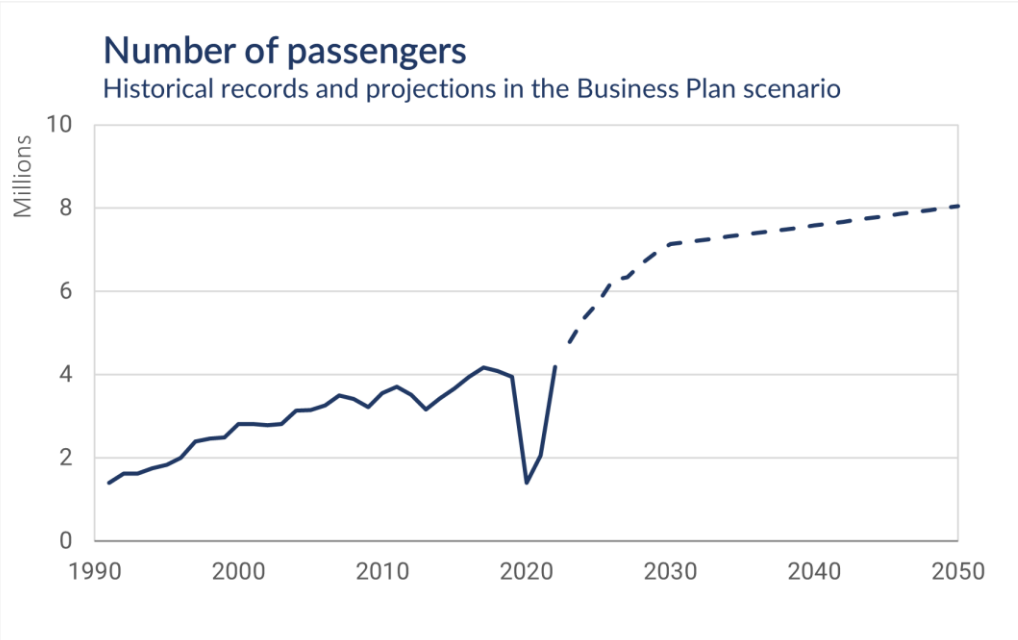


Figure 25 - Number of passengers at Torino Airport according to the Business Plan considered.

8.2.4 The airport energy system

The total volume of the constructions is above 750’000 m^3, with a floor surface of about 170’000 m^2. The main building is the passengers’ terminal, which alone accounts for a volume of 230’000 m^3. The airport also features a second terminal for private flights. The rest of the buildings is various in scope and extension. Some of them are public, such as the covered parking and the remote check-in, while others are offices reserved to employees. Many of them are technical buildings providing support to airport services and aircraft operations such as hangars and the Baggage Handling System (BHS) building.

The airport carries out a multitude of activities in support of the boarding/deboarding of passengers and landing/take-off of flights. The passenger is the main customer on the landside, where several facilities offer a variety of services. Among others, there are the lighting and air conditioning of the buildings, alongside the movement and processing of passengers and baggage. On the airside, the main customer is the aircraft, which is supported in the on-ground operations by a heterogeneous group of Ground Support Equipment (GSE). On this side, typical services include the handling of the aircraft, passengers and cargo, the provision of power to the aircraft through Ground Power Units (GPU) and the maintenance and lighting of the runways.

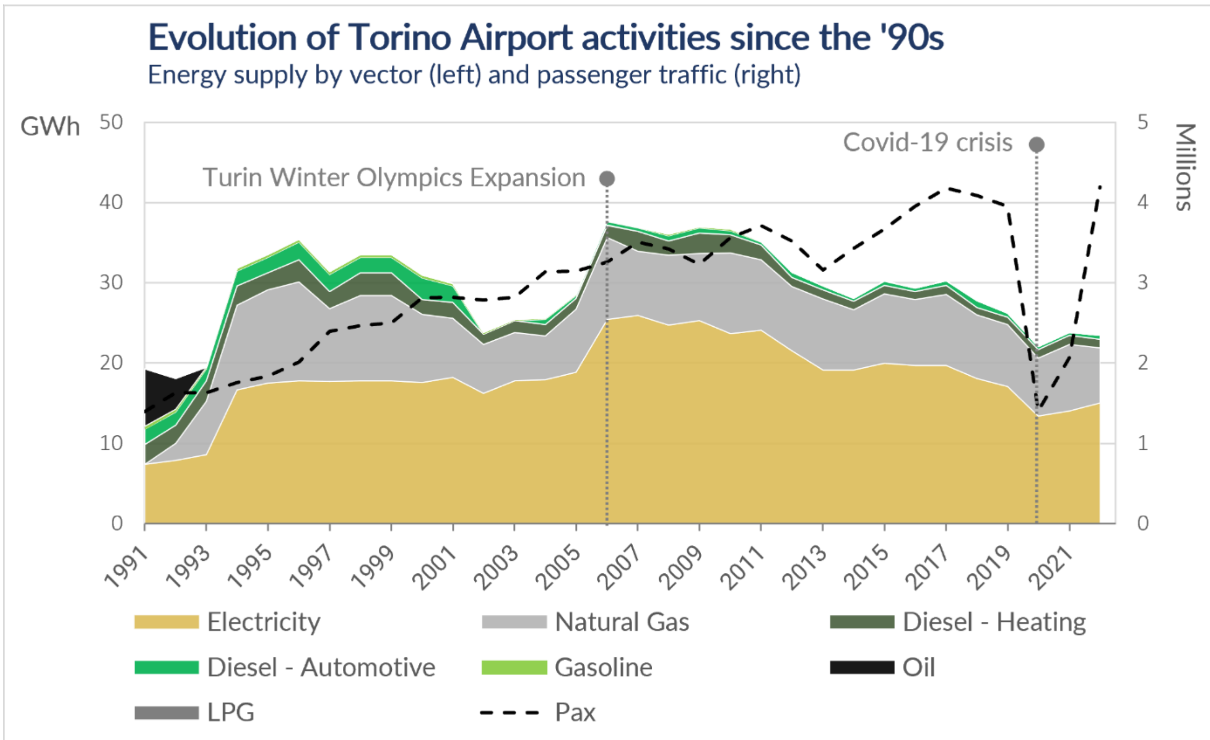


Figure 26 - Historical energy consumption (left axis) and number of passengers (right axis) of Torino Airport's. Energy consumption is reported for each energy vector

In Figure 26, historical energy consumption (left axis) and number of passengers (right axis) of Torino Airport. Energy consumption is reported for each energy vector. In Figure 27the emission sources of the airport are reported for each energy vector.

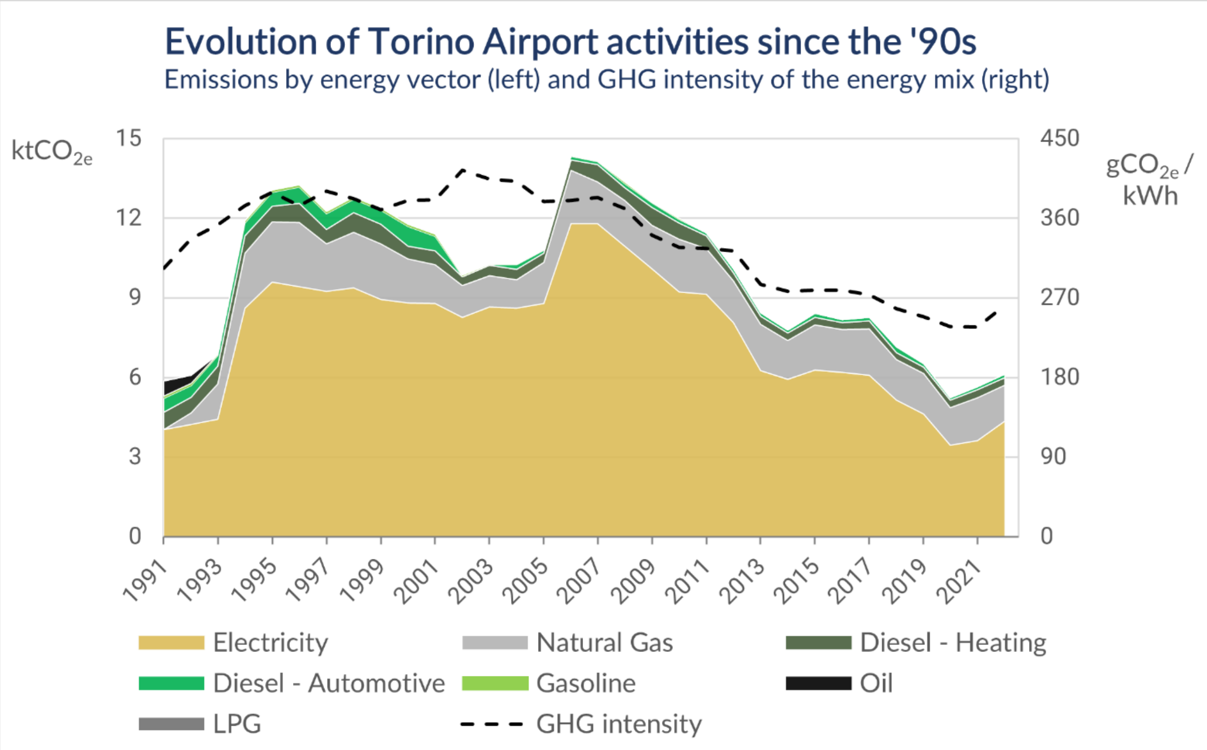


Figure 27 - Historical GHG emissions and targets of Torino Airport. Historical emissions are reported for each energy vector

The airport relies on three main energy vectors: grid electricity, natural gas and fossil diesel. Of these energy vectors, grid electricity alone makes up 80% of primary energy consumption, while natural gas is used only for heating purposes (mainly related to the terminal). LPG and fossil petrol instead constitute a negligible share and are referred to cars and heating of buildings dislocated in peripheral areas where is not economically feasible to use natural gas. As there is no on-site power production, all the resources are imported from outside the airport boundaries.

8.2.4.1 Electrical system

The power station is the main node of the airport electricity network, which is developed from the medium voltage delivery point (27 kV) and is composed of several transformation stations connected in a ring, in order to serve all the low voltage airport users. The decentralized electricity consumers are served with 9 kV main backbones and the low-voltage transformation takes place on site.

The contractual power input for the supply of electrical energy is 5 MW and consumptions are distributed into the three-time segments F1, F2 and F3 quite equally with a predominance on F3 segment due to lighting consumptions.

8.2.4.2 Heating and cooling systems

The airport is served by only one natural gas intake point, which is used to supply the heating systems of the main thermal power plants. The main thermal power plant produces hot water at 90 °C and consists of 3 heat generators with a total rated capacity of 9 MW.

A district heating network brings the heat transfer fluids to the heat exchangers installed in the various sub-stations connected to the main thermal power plant.

The production of chilled water serving the Passenger Terminal is concentrated in 2 refrigeration plants consisting of a total of 5 water/water refrigeration units, with screw compressors and tower water-cooled condensers, for a total installed refrigeration capacity of 7 MW.

The ventilation units serving the Passenger Terminal consist of a total of 30 air handling units. The total flow rate of supply air is 750,000 m3/h.

8.2.4.1 Economic assumptions

As described earlier the methodological framework selected for the study relies on a Net Present Value (NPV) economic analysis. The investment optimisation model selects the configuration of the system which minimises the Total System Discounted Costs (TSDC). The TSDC are composed by several cost items, discounted to the first modelled year. Costs were discounted using a discount rate typical adopted by Torino Airport (reserved information).

The cost items considered in this study are listed in **Error! Reference source not found.**. The economic evaluation included various cost items, from capital costs to revenues generated from the sale of excess renewable electricity back to the grid. Capital costs are assumed to take place at the beginning of the year and discounted accordingly. Other cost items which occur throughout the year, such as the purchase of energy, are discounted to the middle of the year. The residual value of technologies at the end of the modelled period is discounted to the last modelled year. Salvage value is calculated using the sinking fund depreciation method.

Table 6 - Cost items considered in the investment optimisation model. DF: discount factors.

$$Total\ System\ Discounted\ Costs =$$

$\sum_{y,t} Capital\ investment_{y,t} \cdot DF_y +$	Capital costs incurred in year y for the installation of technology t, discounted at the beginning of the year.
$\sum_{y,t} Fixed\ Operating\ costs_{y,t} \cdot DF_y +$	Fixed operating costs (not depending on amount of energy generated, e.g., maintenance costs) incurred in year y for technology t, discounted at the middle of the year.

$\sum_{y,f} Variable\ Operating\ costs_{y,f} \cdot DF_y\ -$	Variable operating costs incurred in year y for the purchase of energy carrier f, discounted at the middle of the year.
$\sum_{y,f} Energy\ sales\ revenues_{y,f} \cdot DF_y\ -$	Revenues generated from the sales of energy carrier f in year y (e.g., sales of excess renewable electricity to the grid).
$\sum_{y} CHP\ incentives\ revenues_{y,CHP} \cdot DF_y\ -$	Revenues in year y from the sales of energy efficiency credits, generated under the high efficiency cogeneration incentive scheme, discounted at the middle of the year.
$\sum_{t} Salvage\ value_t \cdot DF$	Residual value of technology t at the end of the modelled period, discounted at the end of the last modelled year.

A high-level overview of the economic assumptions made for technology and energy prices is presented in Table 7. Data refers to the 2019 baseline year.

Table 7 - Overview of economic assumptions made for Torino Airport. Data refers to 2019 baseline.

Technology price							**Sources**
		Capital cost	Operating cost		Lifetime		
		M€	M€ y^{-1}	*per*			
CCHP		7.62	0.34	*MW_e*	20	*years*	
	SOFC	5.94	0.19[1]	*MW_e*	20	*years*	O&M
	fuel cell	3.26					
	other	2.68					
	Stack replacement	0.95		*MW_e*	40'000	*hours*	
	System and Design	1.68	0.15	*MW_e*	20	*years*	
PV							
	Rooftop	1.44	0.018	*MW*	25	*years*	O&M, [43]
	Ground-mounted	1.01	0.018	*MW*	25	*years*	
Storage and Hydrogen production							
	Battery	0.48		*MWh*	15	*years*	O&M
	Electrolyser	2.6	0.13	*$MW_{H2 (LHV)}$*	40'000	*hours*	
	Hydrogen vessel	0.08		*MWh*	20	*years*	
Heating and cooling							
	A2W Heat Pumps	0.227	0.006	*MW_t*	20	*years*	
Energy carriers							
		Purchase price					
		M€ GWh^{-1}					
Electricity		0.136					Bills
Diesel		0.121					Bills
HVO (from UCO)		0.200					[50]
Diesel oil		0.079					Bills
Natural Gas		0.038					Bills
Biomethane		-[2]					
Hydrogen		0.09 - 0.21[3]					[51]

[1]Include annualised costs for stack replacement
[2]As there is no well-developed market for biomethane, the price assumed for biomethane is better described in the section dealing with scenario assumptions
[3]The range refers to production price of green hydrogen

It is underlined that the analysis did not consider time-sensitive electricity prices. The variation of electricity price throughout the year and the day has proved to be influential on the determination of investment decisions . This is going to become more relevant in future years, when the share of variable renewable generation in the electricity grid is projected to dramatically increase. This situation could also be particularly relevant for Northern Italy, where the general scarcity of wind potential will drive renewable investments mainly towards solar energy, likely generating significant price fluctuations between day and night. However, forecasting such evolution of energy price would require a dedicated study of the future electricity market in Northern Italy, introducing uncertainties in the modelling activity which would be hard to quantify correctly.

As concerns the sale of excess renewable electricity to the grid, the sale of electricity to the grid was assumed to be remunerated at the zonal electricity market price, under the mechanism, namely *Ritiro Dedicato*, set out by the company endorsed by the Italian government for these purposes. In agreement with the directives received by ENAC [23], a constraint on the self-consumption of renewable electricity generated on-site was imposed. Specifically, it was imposed that the airport has to consume at least 70% of the electricity it generates. The electricity sold to tenants and GSE operators was counted towards the self-consumption criteria.

The generation of energy efficiency credits from the operation of the CHP was based on Directive EU 2004/8/EC for high-efficiency cogeneration, implemented by Italian decree DM 08/02/2007. This legislation rewards each unit of primary energy saved by the cogeneration of heat and electricity with respect to separate generation. For each tonne of oil equivalent saved, a certificate (Titolo di Efficienza Energetica, TEE) is emitted. These certificates can then be sold on the dedicated market [54]. In the recent years, the price of a TEE has stabilised to 250 €/toe, which was chosen for the modelling activity.

As concerns biomethane, at present there is no developed market for this product in Italy, although the financial instruments - Guarantees of Origin (GO) - set out by the Italian decree 15/09/2022 are already in place. It can be argued that the price of biomethane would be mainly driven by the will of heavy industries, like steel and cement, to purchase this product. This because biomethane appears as an appealing solution to directly replace natural gas in those energy intensive industries for which electrification is not an option [55]. Since these industries as subjected to the ETS scheme, it can be assumed that the price of biomethane will be linked to that of carbon. It is thus possible to estimate the price of a biomethane GO based on the Willingness-To-Pay (WTP) of these large industries. Specifically, it was assumed that the maximum GO price that an industry would be willing to pay would be equivalent to the price of the emission allowances generated by the substitution of natural gas and biomethane.

8.2.4.2 Baseline scenario

The Baseline scenario aims to describe a *likely* evolution of those elements of the energy system which fall out of the sphere of influence of the airport (e.g., energy and technology price). The scenario is defined within the limits imposed by the unavoidable uncertainties in forecasting the future evolution of large energy systems, which are addressed in the next section.

This section aims to provide a storyline of the *Baseline* scenario (qualitative description) and to describe the main assumptions made (quantitative description).

The *Baseline* scenario assumes that the recent energy crisis prompted by the conflict between Russia and Ukraine will have long-term consequences for the European economy. As such, it is assumed that energy price, in particular for natural gas and electricity, will only slowly recover from the spikes observed in the last years. Even after the recovery, it is assumed that prices will stay higher than they were in 2019. It was also assumed that the price of natural gas and electricity will not be decoupled, although this is arguable, especially in view of large penetration of renewable energy in the power system.

As concerns the development of technological markets, the *Baseline* scenario aims to describe a future compatible with the one depicted by the European policies introduced with the *FitFor55* package [56]. The success of this set of policies would imply the rapid ramp up of the market of emerging technologies (e.g., batteries and fuel cells) and energy carriers (e.g., hydrogen and biomethane) [57]. According to this scenario, the market for these emerging technologies will already be well developed in 2030 [58], bringing investment costs down and driving the technical development of technologies. These considerations will thus affect the economic viability of batteries, fuel cells and electrolysers, while ensuring the availability of supplies of hydrogen and biomethane.

Another important assumption concerns the development of the national power system. It is assumed that, in agreement with Italy's TSO operators' scenarios [59], significant investments in renewable energy sources will take place in the next decades, determining a pronounced decrease of the carbon intensity of grid electricity.

As concerns airport activities, it is assumed that the airport will witness an increase of aircraft operations and number of passengers as foreseen by the Business plan (see Figure 25) The number of passengers will nearly double in 2030 with respect to 2019 levels. Airport activities will keep on growing from 2030 to 2050, but a t a much slower rate.

The following paragraphs present a quantitative description of the *Baseline* scenario.

Electricity demand. It is expected that the electricity demand of the airport will increase due to the increase of airport activities, i.e., air traffic, and the electrification of end-uses. Electrification measures can be endogenously accounted by the investment optimisation model, whereas the additional electricity demand related to increased airport activities must be provided to the model as input data.

The estimation of additional electricity demand was determined taking in account three factors: the increase of air traffic; of aeronautical lighting systems to the jurisdiction of the airport; the electrification of GSE. The latter, which is by all means an electrification measure, was treated exogenously because it is not an investment under the control of the airport, but rather of the GSE operators.

Quantifying the impact of air traffic on the airport's electricity demand required the set-up of a multiple regression model. The model aims to predict electricity demand on the basis of the number of passengers and the average ambient temperature, which were selected from a wider set of operational and weather variables. A categorical variable was included to indicate the periods in which the heating and cooling systems are switched on. The regression model was trained on daily time series for a single year (2019), since the efficiency measures implemented by the airport in the last decade does not allow to perform comparable multi-year analysis. The results of the regression model (see Table 8) show a mild dependency on the number of passengers, with respect to air temperature. It takes about 2000 passengers to increase electricity demand as much as 1 °C in winter, and more than 5000 in summer.

Table 8 - Coefficients and evaluation of the regression model for electricity demand prediction.

Coefficients		
Air temperature		
Heating on	-518	
Cooling on	1393	*kWh/ºC*
All off	28.8	
Passengers	0.247	*kWh/pax*
Model evaluation		
Adjusted R^2	0.90	
Mean Absolute Error	2.7%	

For aeronautical lighting systems, it was assumed that the electricity consumption (about 0.8 GWh) will be passed to the airport before 2030. For GSE, an exogenous electrification rate was assumed, setting a 90% electrification of consumption by 2030 and complete electrification in 2035. The additional electricity demand was calculated using the ratio of efficiency between diesel and electric GSE [60] and scaled to the number of passengers.

The projected growth of electricity demand is reported in Figure 28 for three aviation scenarios. The projection indicated by a dashed blue line refers to the increase of passenger traffic envisaged by Torino Airport *Business Plan* scenario, whereas the *Low* and *High* projections are based on top-down scenarios prepared by ENAC [61]. Different aviation scenarios have low impact on the increased electricity demand, thus only the *Business Plan* scenario was considered for the analysis. However, it is worth remarking that the increased electricity demand only refers to *Scope 2* consumption of the airport. The electrification of activities falling under the *Scope 3* category, among which electrification of airplanes and ground operations are particularly representative, would significantly affect the sensitivity of electricity demand to air traffic. However, this analysis is out of the scope of this study.

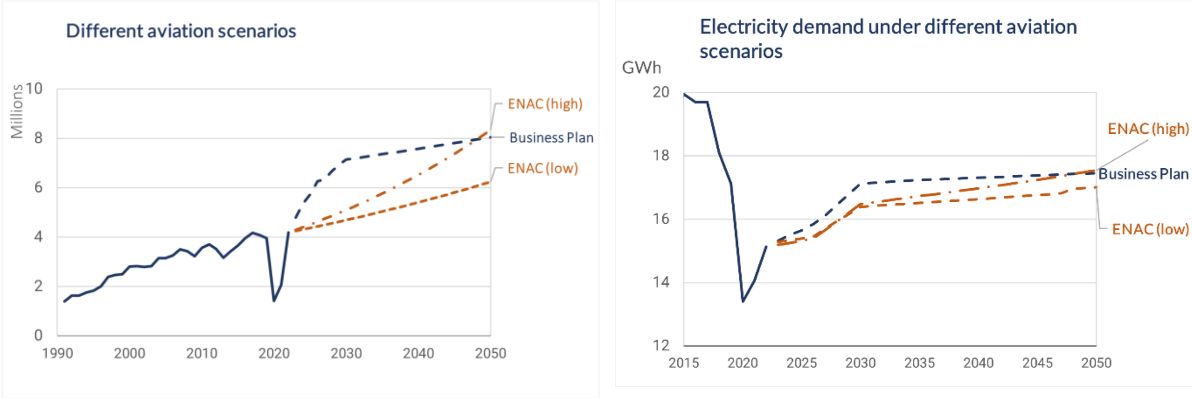


Figure 28 – Electricity demand projections under different aviation scenarios for Torino Airport. N.B., electricity demand projections do not include effects related to electrification of heating and transport activities, which are endogenously determined by the model.

<u>*Energy price*</u>. One major modelling choice undoubtedly concerns the evolution of energy price. The instability of these markets makes hard to predict their future prices, especially afterwards the energy crises triggered in the last years. Therefore, in this study conservative assumptions were made on the energy markets. In particular, it was assumed that the Ukrainian-Russian conflict will prompt structural changes in the European energy markets, affecting the price of electricity and natural gas in the long-term too. The price of these two commodities was imagined to recover from the spikes observed after 2022, but it was assumed that their price after 2030 will still be higher than in 2019. No decoupling between electricity and natural gas markets was assumed, due to uncertainties on how the energy transition will affect this link. For diesel and heating gas oil, the price was projected to grow with the same linear trend which has characterised oil products in Italy in the last decades [62], compatible with the price index used in European models [56]. **Error! Reference source not found.** reports the price assumptions for milestone years.

Table 9 - Price projections for relevant energy commodities at Torino Airport.

Year	Electricity	Natural gas	Diesel	Heating gas oil
	€/MWh (index to 2019 reference)			
2019 (ref.)	136 (1.00)	38 (1.00)	122 (1.00)	79 (1.00)
2025	279 (2.05)	89 (2.33)	150 (1.23)	94 (1.19)
2030	212 (1.56)	46 (1.21)	165 (1.36)	103 (1.30)
2040	227 (1.67)	46 (1.22)	196 (1.61)	120 (1.52)
2050	232 (1.70)	49 (1.28)	228 (1.87)	138 (1.74)

<u>*Biomethane price*</u>. Although the market platform for the exchange of biomethane guarantees of origin (GO) is already in place in Italy, it is not yet active. Therefore, no reference is available to determine the present price of biomethane. This will be likely dependent on the willingness to pay (WTP) of large energy consumers, in particular heavy industries and transport subjected to the ETS scheme [55], which could see in this renewable fuel a valid option to decarbonise their energy system and decrease reliance on fossil imports [63]. Therefore, biomethane GO price was

estimated as the WTP of the se consumers and linked to the carbon price. Specifically, it was assumed that buyers would be willing to pay an additional price for biomethane equivalent to the amount of emission allowances generated by the displacement of fossil gas with this renewable fuel. The carbon price projections were based on literature projections [64]. Price assumptions are reported in Table 10.

Table 10 - Scenario assumptions on the development of the price of carbon and relative biomethane GO price for Torino Airport.

Year	**Carbon price** €/MWh	**Biomethane GO price** €/MWh
2019 (ref.)	20	-
2025	105	19.4
2030	113	21.9
2040	115	22.3
2050	115	22.3

<u>Hydrogen deployment scenarios</u>. The high initial investment required by hydrogen technologies represent to date the main economic barrier for their uptake. This is mostly related to the infant stage of the market. Nevertheless, if the targets set by EU's *Hydrogen Strategy* [58] will come to reality, the market for hydrogen production and end-use technologies will rapidly soar, sprawling already before 2030. This will likely drive initial investment costs down, as observed for other emergent technologies, like PV and Wind, during the last decade [43]. In addition, it seems plausible that the build-up of the industrial capacity needed to satisfy market demand for hydrogen technologies will foster research and innovation in the field. This would lead to the improvement of technical aspects such as efficiency and lifetime, mimicking the rise of efficiency observed for PV technologies [65].

To quantify the extent to which hydrogen technologies will be affected by this development is a cumbersome task. For the purpose of this analysis, a *High Hydrogen Deployment* scenario was designed, based on the same assumptions made by the IEA report on hydrogen perspectives [44] and corroborated by other scientific references [46]. The designed scenario (Table 11 assumes a decline of CAPEX by as much as 70% already in 2030, and 80% in 2040. The lifetime of fuel cell and electrolyser stack increases, from 40'000 to over 60'000 hours, reducing the OPEX related to replacement. The efficiency of the electrolyser rises from the current 62.5% to nearly 73%.

Table 11 - Overview of scenario assumptions on the development of technology market for Torino Airport.

	Capital cost	Operating cost		Lifetime		Efficiency	
	M€	M€ y^{-1}	*per*				
CCHP[1]							
2019	7.62	0.34		40'000			
2031-2040	6.67	0.29	*MWe*	60'000	*hours*		
2041-2050	5.72	0.29		60'000			
Electrolyser							
2019	2.60	0.13		40'000		0.63	
2031-2040	0.80	0.04	$MW_{H2\,(LHV)}$	75'000	*hours*	0.70	$MW_{H2\,(LHV)}\,MWe^{-1}$
2041-2050	0.64	0.03		75'000		0.73	
Battery							
2019	0.48						
2031-2040	0.22		*MWh*				
2041-2050	0.11						

[1]Price reduction was only applied to the SOFC components.

External hydrogen supply. The availability of an external hydrogen supply in future years will depend on the development of the surrounding energy system of the airport. In particular, the integration of the airport in a local hydrogen valley – an emerging concept in the Piedmont region – appears as a plausible future scenario. In this work, a specific pathway describing the integration of Torino Airport in such a local hydrogen economy as simulated. The availability of an external hydrogen supply was assumed only after 2040, since the present projects are at an infant stage and the realisation of the necessary hydrogen infrastructures would require a significant amount of time. As concerns the price, it is out of the scope of this Work Package to delineate detailed hydrogen supply routes, which has already been investigated by several literature works [29, 66] and will be more specifically addressed by Work Package 4. In this analysis, a levelized cost of hydrogen of 2 €/kg (about 60 €/MWh), including the price related to the transport of hydrogen from production sources to the airport, was assumed. It is noted that a relatively affordable price was considered, compatibly with the projected decline in hydrogen production costs [45, 67]. Anyway, it should be noted that hydrogen price is significantly affected by the transport modality and the amount transported, so the assumptions made aim to depict an optimistic scenario for hydrogen development.

Battery price. As concerns the price of Li-ion batteries, decreasing trends similar to those assumed for hydrogen technologies were projected (Table 11**Error! Reference source not found.**). These long-term projections were largely based on the price indices forecast by an IRENA study on the development of behind-the-meter batteries [68].

Grid decarbonisation. Electricity is presently the primary energy source of the airport, while its role is poised to even increase as the electrification of end-uses progresses. Investments in on-site generation of electricity from solar energy is expected to provide a clean source to support this development. However, renewable generation would be concentrated in the central hours of the day, so that the electricity demand of the airport could not be entirely satisfied by on-site renewable generation. Although this mismatch could be averted with the massive integration of storage technologies, the capital costs to secure an uninterrupted supply of clean energy would be exorbitant.

This given, it seems clear that the airport will continue to rely on the utility grid for a non-negligible share of its electricity demand. It is therefore pivotal to correctly represent the evolution of this fundamental piece of the energy system. In particular, the projection of grid carbon intensity should be considered in a model with a time horizon of several decades, as it could affect investment choices, especially under tight decarbonisation targets. For example, technologies which today present themselves as competitive decarbonisation options (e.g., PV and CCHP) in the future could become more expensive than the purchase of low carbon electricity. Conversely, electrification measures would become more appealing in face of a highly decarbonised grid.

For the analysis carried out in this work, a simple model of the Italian electricity system was realised with the aim to project grid carbon intensity in future years. The model builds on the TERNA-SNAM scenarios [59], which project the expansion of the Italian grid till 2040, providing information on installed renewable capacity and energy mix. Specifically, the GA scenario was selected. Based on the methodology developed by ISPRA [12], the grid mix was used to estimate the carbon intensity of the grid in the future years. For the import components of, which represents non-negligible 15% of Italy's gross consumption of electricity [69], it was assumed that the carbon intensity of exporting countries will linearly decrease till reaching zero emissions in 2050. For the period 2040-2050, not covered by TERNA-SNAM scenarios, a linear decrease till the achievement of zero emissions in 2050 was assumed. This can be considered a conservative assumption, as the achievement of EU's targets for a net-zero society would need to rely on a highly decarbonised power system, which could reach zero emissions even before the 2050 deadline.

The resulting carbon intensity is reported in Figure 29 - Projection of carbon intensity of grid electricity in Italy. Based on TERNA-SNAM scenarios and calculated according to ISPRA's methodology..

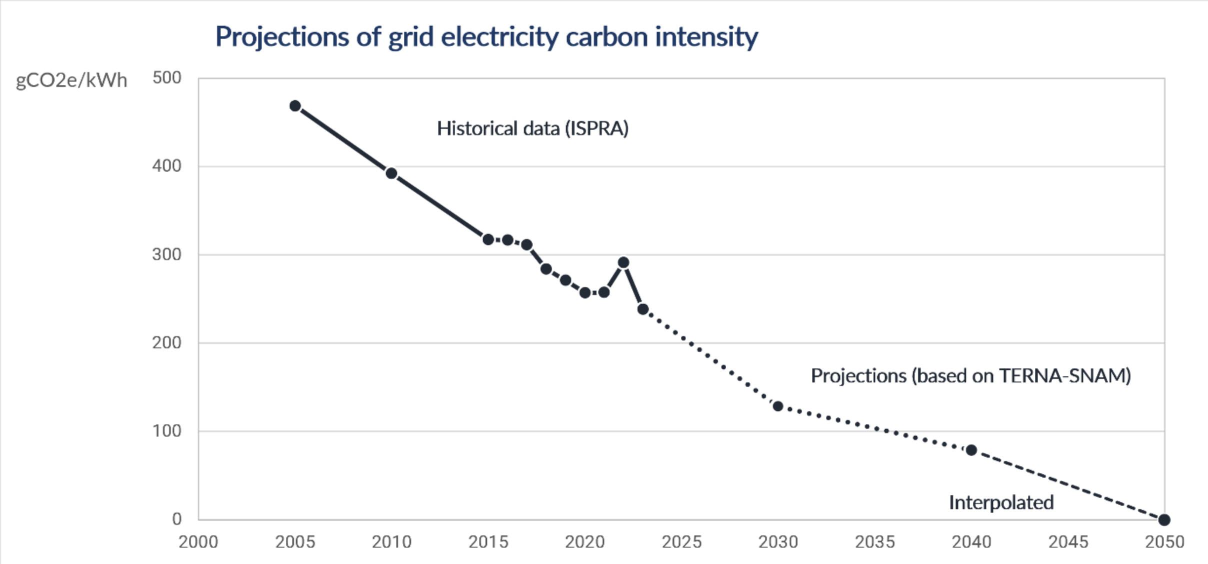


Figure 29 - Projection of carbon intensity of grid electricity in Italy. Based on TERNA-SNAM scenarios and calculated according to ISPRA's methodology.

8.3 Introduction to Stavanger airport Sola

8.3.1 General introduction of Stavanger airport

The Stavanger airport Sola (IATA-SVG, ICAO-ENZV) is one of the principal airports in Norway with almost four million passengers in 2023 [30]. In addition to international and domestic flights, Sola is the main helicopter hub for the South-western part of Norway, serving the Norwegian offshore petroleum sector in the North sea. The total number of air traffic movements in the airport was approximately 71 thousand in 2023, where offshore helicopter traffic counted for 16 thousand.

Organisationally the airport is a part of the Avinor group, wholly owned state limited company under the Norwegian Ministry of Transport and Communications which operates 43 airports in Norway with app. 50 million passengers annually.

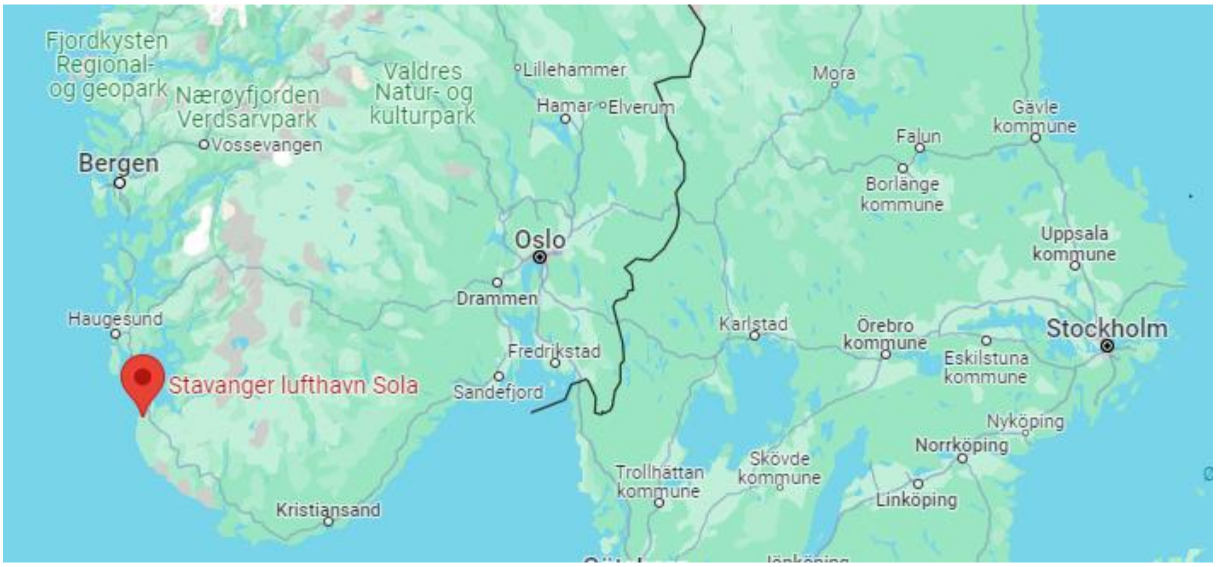


Figure 30 Location of Stavanger Airport Sola. Source: https://www.google.com/maps

The airport is located 15 km south-west from Stavanger city (see Figure 30) at latitude 58.88045 and longitude 5.63143 and has two runways: 18/36 and 10/28 (see Figure 32where the secondary runway (10/28) is used when the primary runway (18/36) is closed for any reason i.e. due to maintenance or during certain wind conditions [31] and helicopter traffic.

Climate in Stavanger is influenced by the proximity to the North sea and Gulfstream ocean current. Considering the geographic location, the climate therefore can be considered as fairly mild with average annual temperature around 7°C[14] and precipitation of 1 180 mm [32].

[14] https://www.met.no/

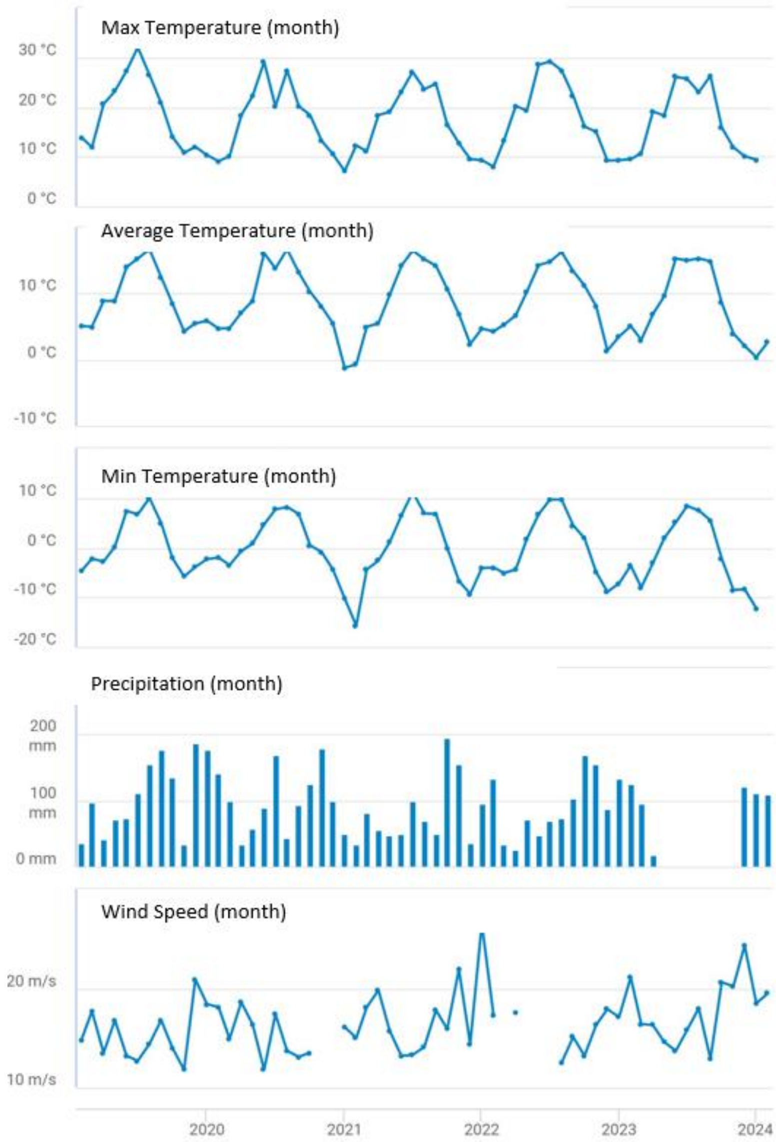


Figure 31 Weather data for Stavanger Airport Sola. Source: seklima.met.no for SN44560, Sola.

Figure 31 shows an overview over historical data for five consequent years. It is noticeable, that due to its location the airport is exposed to winds and storms from the North sea, especially during winter season.

Figure 32 Aerial view of the airport showing airport complex and region of consideration.

The historic energy consumption figures are presented in Table 12

Table 12 Main characteristics for Stavanger airport. Source: [31]

	2012	2019	2021	2022
Areal (buildings) [m2]	49 872	60 945	60 945	60 945
Energy costs [kNOK]	8 450	12 440	11 940	33 500
Electricity [kWh]	17 364 488	15 186 434	13 197 001	13 543 238
Auxiliary power [kWh]	413 215	204 701	272 505	220 446
District heating [kWh]	2 215 866	2 701 199	3 358 696	3 035 586
Consumption [kWh]	19 993 569	18 092 334	16 828 292	16 799 270
Consumption [kW/m2]	401	297	276	276

8.3.2 Airport climate footprint and ambitions

As a part of its environmental policy Avinor participates in both national and European Research and Innovation projects in collaboration with start-up companies, academia, research and educational institutions and public and private businesses. Apart from TULIPS Stavanger airport has participated in a six-year innovation and demonstration project Elnett21[15] [33], where large stakeholders such as port, industrial park, the airport and the regional power grid operator are working together to prepare themselves for the large power outlets that electrification will entail. The aim is that local energy production and storage, smart energy control system and regional co-operation will quickly lead to a successful electrification of transport and reduce/stabilise the burden on the power grid. Outcomes of Elnett21 have been used as basis for creation of the target scenarios for Stavanger airport in TULIPS.

Being a part of the Avinor group, Stavanger airport is aligned with the official corporate environmental goals, which were approved in October 2023 [34]. Within these the most relevant part for the scope of present project is the goal of collaborating with the rest of the aviation industry and facilitating the Norwegian aviation sector's goal of being fossil-free by 2050. Stavanger airport was officially climate certified in the international Airport Carbon Accreditation (ACA) scheme in 2014 and works purposefully to reduce CO2 emissions from its own operations [35].

8.3.3 Airport business scenarios

The Avinor's Corporate Policy demonstrates strong commitments to the climate goals and sustainable operation. In Avinor's group strategy for the period 2022-2025, the company sets a clear ambition to be an active supporter of sustainable aviation enabling the Norwegian aviation to reach its goal to be fossil-free by 2050, while Avinor's own operations aim to become fossil-free already in 2030.

Avinor has expressed its intentions for reducing the greenhouse emission by electrification, including the operation of infrastructure such as buildings and facilities, motorised transportation at airports, and air traffic itself. Based on the information, which Avinor has obtained from aircraft manufacturers, it is a realistic expectation that the first electrified aircraft could enter the testing and development phase in domestic passenger services in Norway around 2026 and that the first flights could be electrified from 2027-28 before entering wider scheduled service around 2030.

It is necessary to mention that interest to introduction of the electric aircrafts in Norway in many ways is motivated by the domestic landscape i.e. mountainous terrain with most of the population, industry and major cities located along lengthy coastline divided by numerous fjords, islands and bays. This makes travelling between the cities by car very time-consuming. Building new infrastructure for railway is for the same reason both time consuming, costly and will introduce large impact om the environment. This makes air traffic a preferred passenger transport. It is estimated that more than 20 destinations/routes in the Norwegian short airfield network have distances ranging from 38 – 170 km, while driving distance would be several times longer. These routes are very good candidates for introduction of battery-powered electric aircrafts (including VTOLs).

[15] https://www.elnett21.no/

8.4 Larnaca Airport – scenario study and system design concepts

8.4.1. Introduction to the airport

8.4.1.1 General introduction of Larnaka airport

Figure 33, Larnaka Airport Aerial Photo

The Larnaka International Airport has been operated by Hermes Airports Ltd. since 12th May 2006 based on a 25-year Build-Operate-Transfer (BOT) concession agreement with the Republic of Cyprus. The construction of the new terminal was completed in 2009 with its inaugural operation taking place in November of the same year. Through the concession agreement there is a second phase construction plan of extension of the airports' facilities, that will take place once traffic numbers reach specific agreed thresholds.

Situated on the southeastern coast of the island, the airport occupies a total area of 603 hectares. The terminal spans 100,000m², catering to category E aircraft. It has a single runway (04/22) measuring 2,994 meters in length and operates round-the-clock, year-round.

The airport features 28 aircraft parking stands for commercial aviation/movements, 8 bus/remote gates, and 16 passenger boarding bridges.

Since January 2010, the airport has served over 82 million passengers, averaging six million annually, with Hermes Airports contributing 3% to the national GDP. Passenger traffic over the past five years is outlined in the table below. More than 4,500 persons are employed by airport's organizations and companies, while Hermes Airport, as the operator of Larnaka International Airport employees around 140 people.

Year	Passenger Traffic
2019	8,229,346
2020	1,679,807
2021	3,591,997
2022	6,037,133
2023	8,073,932

The airport is structured across five floors. The basement houses general operational facilities, maintenance and offices, while the ground floor hosts bus/remote gates, maintenance offices, arrival baggage reclaim, meet and greet areas, as well as shops, restaurants, and other offices. Level one serves as the arrivals area and facilities various offices. The departures section occupies the second floor, featuring shops, restaurants, offices, check-in counters, security areas, and gates. Offices and mechanical rooms are situated on the third level.

Externally, the airport offers over 2,500 parking spaces, along with offices, electric vehicle charging stations, cafes, and supplementary buildings and services. These include the air traffic control tower, fire brigade building, cargo sheds, maintenance facilities, aircraft hangars, and maintenance stations.

Figure 34, Map of Cyprus with the location of Larnaka International Airport

8.4.1.1.1 Hermes Vision

Hermes Airports is committed to leading initiatives aimed at mitigating global warming in accordance with the Paris Agreement. This involves enhancing energy efficiency, managing and reducing greenhouse gas emissions, and optimizing the utilization of natural resources. This commitment aligns with the goal of achieving net zero emissions by 2050, maximizing efforts toward decarbonization.

8.4.1.1.2 Airport's Environmental Policies

With the anticipated growth in air travel expected to continue in the coming decades, the aviation sector faces the imperative of developing tools necessary to mitigate, regulate, and monitor greenhouse gas emissions associated with airport operations.

To maintain environmentally responsible practices, Hermes Airports Ltd adheres to a defined Environmental Policy, which sets clear objectives for emissions and pollution management. The primary goal is to manage energy usage and greenhouse gas emissions actively, thereby reducing the environmental footprint of operations. Therefore, it is imperative for Hermes to:

- Optimize energy usage in a manner that is efficient, cost-effective, and environmentally sustainable.
- Minimize the environmental footprint of airport operations and activities.
- Explore and implement green energy solutions that benefit airports, stakeholders, and communities while enhancing community awareness and involvement.
- Ensure compliance with all relevant laws and regulations.
- Promote and work towards greener and eco-friendly airports and the environmental protection as part of Hermes' ESG (Environmental, Social, and Governance) responsibility.
- Implement strategies and measures to conserve energy, reduce carbon emissions, and mitigate the environmental impact of airport operations.
- Maximise the utilisation of the renewable energies in Hermes' energy mix

8.4.1.1.3 Climate in Cyprus

Cyprus has a Mediterranean climate, which means it generally experiences hot, dry summers and mild, wet winters.

Summers are typically long, hot, and dry, with temperatures often exceeding 30°C and sometimes reaching as high as 40°C. Rainfall is minimal during this time, and the island receives abundant sunshine. Winters are mild and relatively wet, with temperatures rarely dropping below 10°C in coastal areas. Rainfall occurs mainly between November and March, although it can be sporadic. Spring and autumn are transitional seasons, with mild temperatures and occasional rainfall.

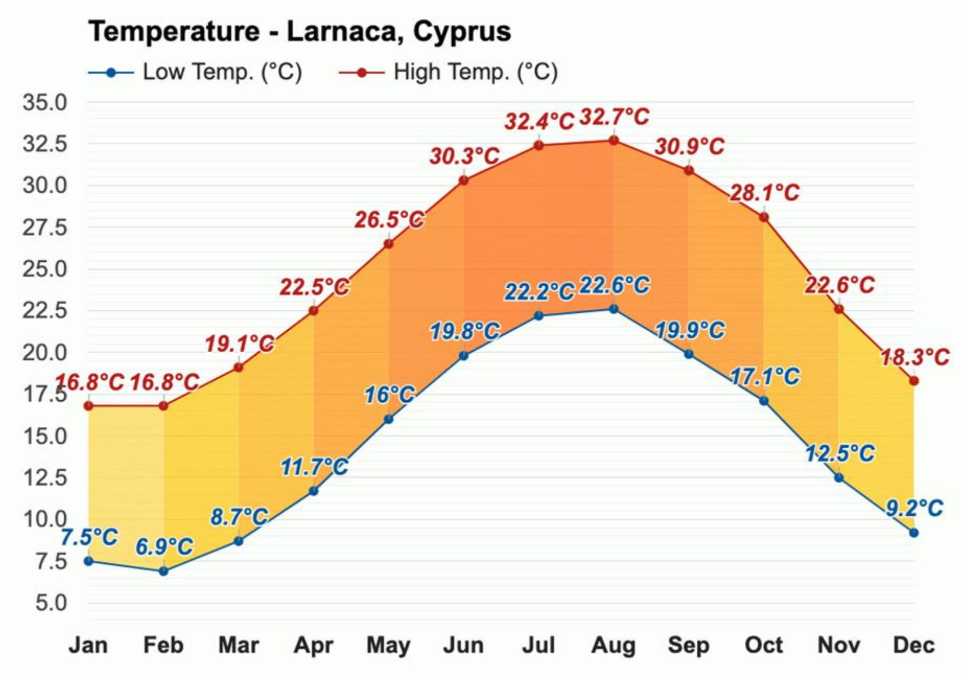


Figure 35, Larnaca annual temperature profile.

8.4.1.1.4 Energy Types

Due to the limited scale and the isolation of Cyprus's energy grid from mainland Europe, there exists a high carbon intensity, with only a small portion of renewables being utilized. According to the latest data from the Transmission System Operator of Cyprus, renewable energies such as wind and solar power account for only 15.6% of Cyprus's total energy production, while the remaining 84.4% is generated through the burning of fossil fuels.

This situation, combined with the absence of energy storage technologies on the island, results in a high carbon dioxide emission factor for each kilowatt-hour produced or consumed.

The following figures provide a graphical comparison of the carbon intensity of Cyprus and the rest of the Europe.

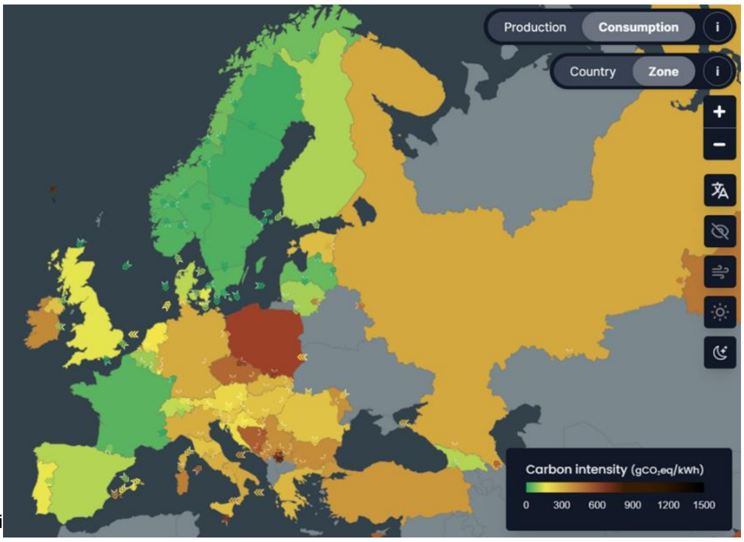


Figure 36, Carbon Intensity of Cyprus and the rest of the Europe.

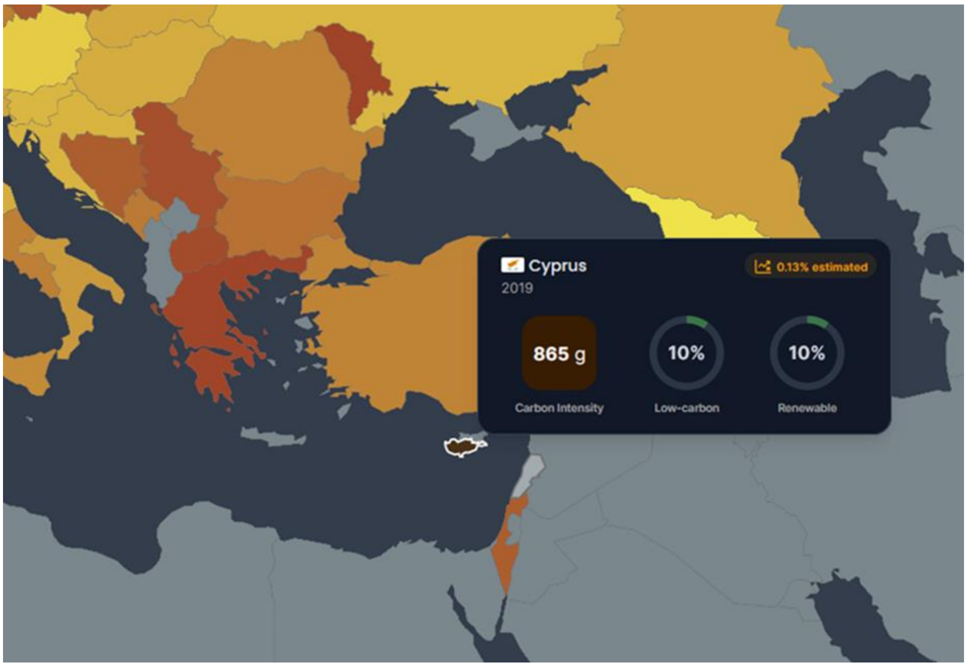


Figure 37, Carbon Intensity of Cyprus.

<u>Photovoltaics</u>

Hermes has developed a 3.5 MWp PV plant at Larnaka International Airport as part of its carbon reduction plan. The on-site photovoltaic plant contributes to approximately 28% of the airport's energy requirements and reduce the carbon emissions of the airport by more than 3,600 tons of carbon dioxide equivalent emissions per year. The existing plant occupies an area of 36,000m².

Figure 38, Larnaca Photovoltaic (solar) Park

8.4.1.2 Airport climate footprint and ambitions

Current Status and Footprint

During the initial ten years of operating the new terminal at Larnaka International Airport, Hermes made substantial investments in energy and carbon management, reflecting its fundamental environmental values.

As a pioneer in the field, Hermes achieved certification to ISO 50001 Energy Management System standard in December 2016, placing it among the very first airports globally to attain this EMS standard. The system was upgraded to the latest version in 2019 (ISO 50001:2018). Moreover, the company holds certifications in ISO 14001 Environmental Management System and EMAS (Eco Management and Audit Scheme).

In December 2016, the airport entered the Airport Carbon Accreditation programme of ACI at Level 1 "Mapping" and, within two and a half years, attained the highest level of accreditation, Level 3+ "Neutrality" by June 2018. In April 2024 Larnaka Airport was accredited to Level 4+ ” Transition”.

The company has received three awards during the Cyprus Green Procurement and Purchase Awards in December 2017, recognized for "General Policy," "Internal Lighting," and "Energy Performance of Building Facilities."

During the first Business4Climate awards, hosted by the Cyprus Ministry of Agriculture, Rural Development and Environment, Cyprus Employers and Industrialists Federation (OEB), and the Cyprus University of Technology, Hermes received two out of three awards for "Outstanding

Performance in the reduction of carbon emissions" and "Collaboration with other businesses and entities for the reduction of carbon emissions."

Hermes' Carbon Footprint is attributed to a great part on energy consumption. Efforts and initiatives undertaken from 2010 to 2019 focused on reducing this component, which accounts for 96% of emissions directly managed by Hermes.

The focus concentrated in the improvement of energy efficiency through various actions such as:

- Implementation of LED-technology in the lighting systems
- Energy management, metering and control
- Heating, Ventilation and Air-Conditioning system optimization and upgrade
- Building envelope improvement
- Development of an Advance Building Management and Control System
- System utilization and control through real time sensor calibration, scheduling and occupancy sensing, taking into consideration a series of parameters and aspects to improve systems' efficiency.

Figure 39, Hermes Sustainability Achievements 2010-2019

The achievement in the reduction of energy resulted to a significant carbon emissions equivalent reduction in the last decade, through the implementation of a series of initiatives and actions as described above. The reduction is presented below with year-over-year comparison.

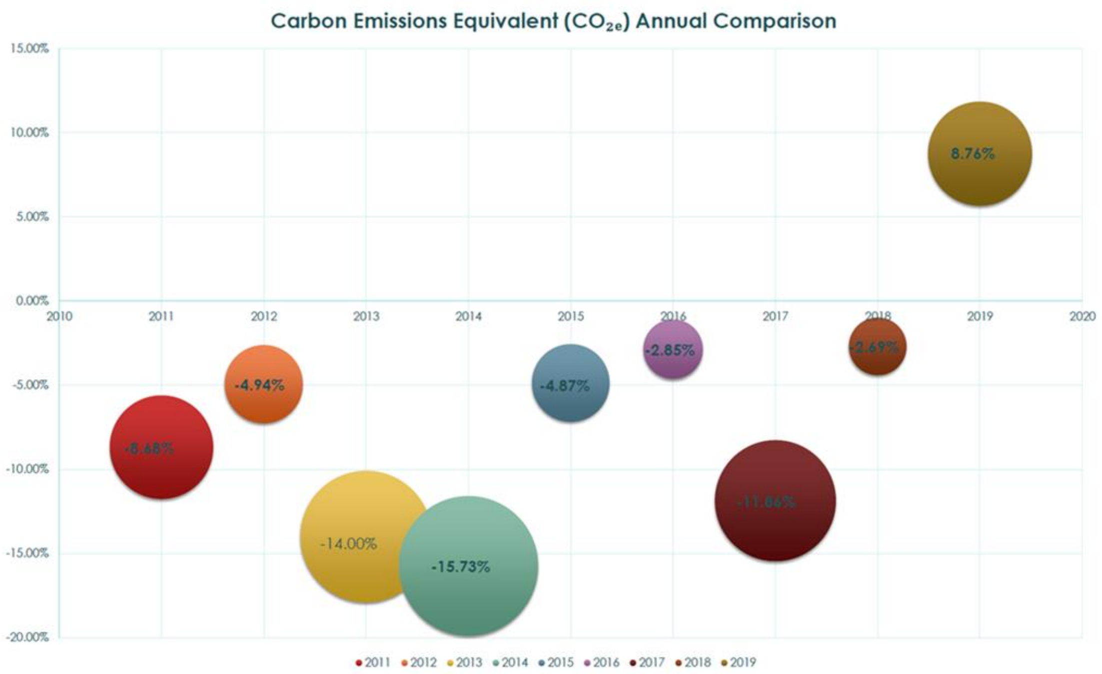


Figure 40, Carbon Emissions reductions

<u>Airport's Ambitions, Objectives and Roadmap</u>

In order to ensure sustainability is integrated into the business model and all parameters are addressed, Hermes has set up policies, strategy and strategic objectives using as reference the United Nations Sustainable Development Goals (UN SDGs), ACI Directives, and Cyprus National Action Plan.

These are transformed into a road map with Short, Medium and Long-Term objectives, targets and actions that would lead to the ultimate target of Net Zero. These are to be tracked and reviewed on an annual basis.

The main pylons of Hermes' Energy and Climate Strategy are focusing on the:

- Climate Change
- Energy Efficiency
- Clean Energy

Sustainable climate and energy management form part of the overall sustainability strategy of the Company.

Hermes has set these goals with the 2050 horizon however the intention is to monitor and replan so that their fulfilment could be achieved much earlier.

The roadmap of Hermes covers the majority of the planned actions and initiatives as presented in the existing strategy and translated into the following roadmap.

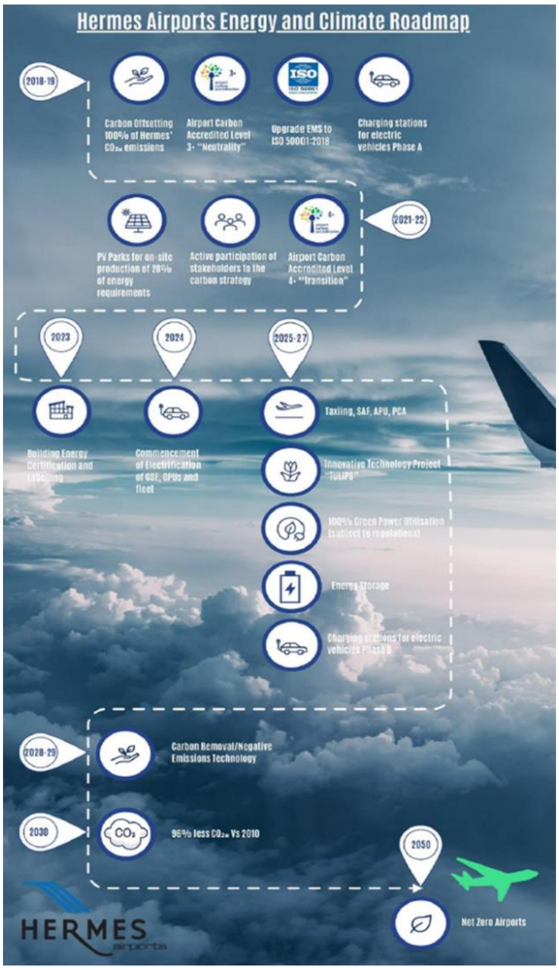


Figure 41, Hermes Energy and Climate Roadmap

Hermes' Pathway to a Green Future

Hermes' roadmap as developed in combination with the various initiatives identified led to the following green pathway as presented in the following graph.

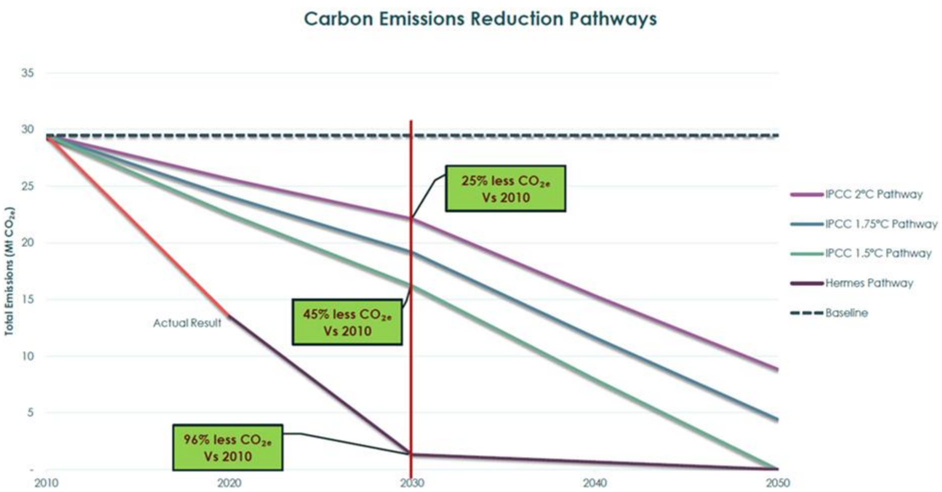


Figure 42, Carbon Emissions Reduction Pathways

The projects in Hermes' pipeline are anticipated to yield a substantial reduction in carbon dioxide equivalent emissions, amounting to 96% compared to the baseline year of 2010. This translates to nearly double the reduction in carbon emissions compared to the most optimistic scenario outlined in the Paris Agreement. According to the IPCC 1.5°C scenario, emissions are projected to decrease by 45% by 2030 compared to 2010 levels, while Hermes's plan is aiming to a 96% reduction in the same period.

Hermes' Carbon Footprint is attributed to a great part on energy consumption. The initiatives and actions in the period of 2010-19 were focused on the reduction of this element which corresponds to 96% of the emissions directly controlled by Hermes, as described above. The following graph provides a graphical representation of Hermes' directly controlled emissions.

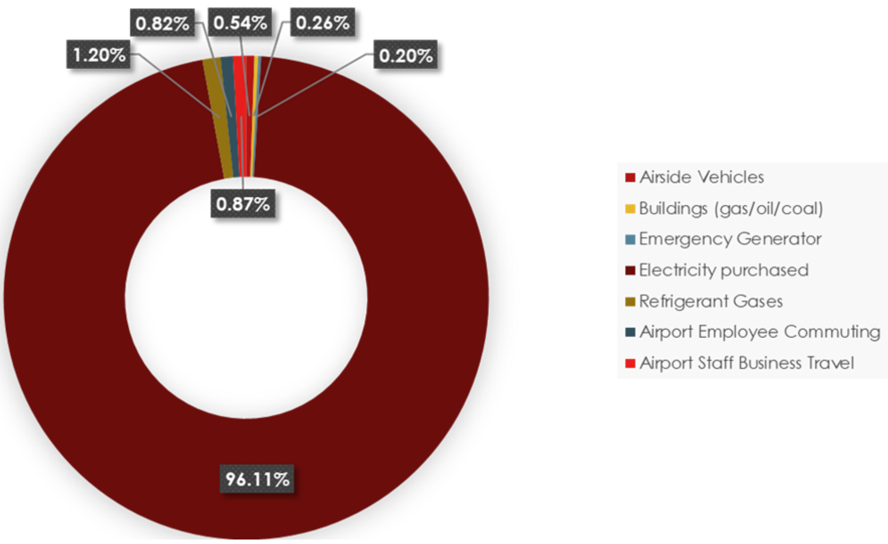


Figure 43, Hermes directly controlled CO2 emissions

By incorporating the indirect emissions (Scope 3) of the airport into the total airport's footprint, the percentage per emission source is significantly affected. Hermes controls only 8.5% of these emissions.

The main sources of the emissions are:

- Aircraft Landing, Taxiing, Take-off (36.9%)
- Public Access-Commuting (36.6%)
- Electricity Purchased (8.7%)
- Staff and visitors (8.5%)
- Aircrafts APUs (5.3%)
- Fleet (1.3%)
- Rest (2.6%)

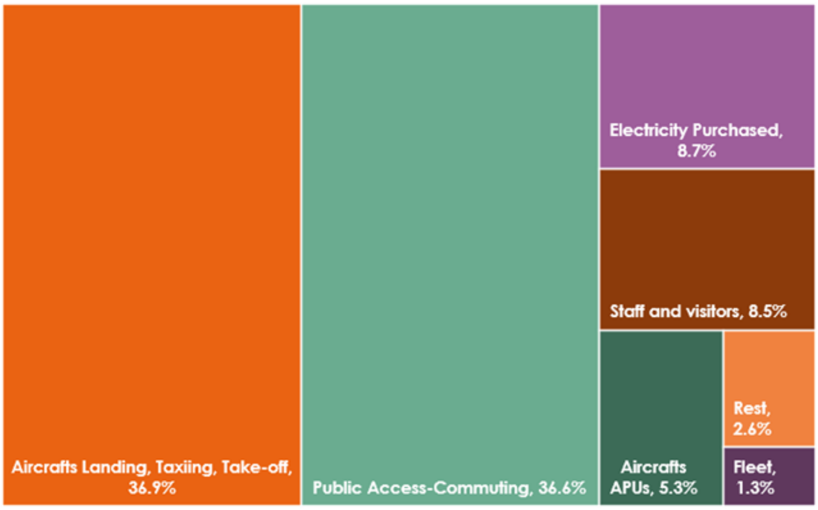


Figure 44, Sources of CO2 Emissions at Larnaka International Airport

The following table summarises the total Carbon Dioxide Equivalent Emissions of the Larnaka International Airport for the entire period such data is available.

Scope 1&2 Emissions	**2014 (tCO_{2e})**	**2015 (tCO_{2e})**	**2016 (tCO_{2e})**	**2017 (tCO_{2e})**	**2018 (tCO_{2e})**	**2019 (tCO_{2e})**	**2020 (tCO_{2e})**	**2021 (tCO_{2e})**	**2022 (tCO_{2e})**
Airside Vehicles	88.99	63.43	83.76	79.06	83.46	94.48	95.54	94.78	95.7
Airside Vehicles Kerosene	58.10	56.41	25.88	57.79	0.00	0.00	0.00	0.00	0.00
Buildings	72.70	80.70	76.40	68.90	40.09	65.86	40.36	42.35	56.5
Fire Training	37.50	52.40	55.00	30.44	0.00	30.88	0.00	29.41	0.00
Emergency Generator	9.50	32.90	23.30	22.76	30.52	9.18	9.00	28.99	37.3
Airport Scope 1	266.8	285.5	264.3	259	154.1	200.4	144.9	195.5	189.5
Airport Scope 2	16,839	15,691	15,317	14,845	14,867	15,099	13,915	0	10,092
Refrigerant-Scope 1	583.6	532.4	516.3	530	186.2	97.5	0.00	239.2	134.7
Airport Operator Total CO_2e emissions	17,534	16,509	16.098	15,634	15,207	15,397	14,060	434.7	10,417
Airpo Airport Scope 3	n/a	n/a	n/a	n/a	174,695	171,841	169,084	101,116	506,931

Table 13, Larnaca Airport Carbon Dioxide Equivalent Emissions 2014-2022

8.4.1.3 Airport business scenarios

The business plan of Hermes has been analysed in the preparation of the simulation system for the future scenarios. This plan dictates several factors and parameters to be considered in the final system, such as:

- Five milestone years: the milestone years analyzed during the simulation includes the baseline year of 2019, the first intermediate milestone of 2027 (3 years after the finalization of the simulation), year 2030 (the last full year of Hermes' Concession Agreement for the operation of Larnaka International Airport), the 2040 year as an intermediate step towards the final/long-term target year of 2050. The final milestone is aligned with the net-zero target year of Hermes.

- Passenger traffic increase: Forecast of the passenger traffic shows an expected increase of approximately 2% per year. This was kept constant for the entire duration of the project and the scenarios for all milestone years.
- Meteorological conditions as per IPCC – RCP 2.6 as described above.
- Electrification of Hermes' own vehicles/fleet from 2024 onwards.
- Electrification of ground support equipment operating at the airport as per current Ground Handling rules. The rules dictate the replacement of 30% of the GSE every three years with electric equipment, aiming to fully decarbonization of the equipment until 2030.
- Photovoltaic plants capacity increase by 1.2MWp from the first milestone year, thus resulting to a system of 4.7MWp from 2027 onwards. Energy storage solutions also forms part of this scenario.

8.4.2 Methodology

8.4.2.1 Methodological framework used for the scenario analysis.

As carbon emissions are strongly linked to energy consumption in Cyprus, the following methodology focuses on reducing the power grid consumption of the airport to achieve carbon reduction goal. The methodology is based on the following steps:

Modelling the airport and its consumptions:

Collection and analysis of historic data (electricity, fuels, carbon emissions)

- Historic data on passenger traffic, staff, cargo and aircraft movements.
- Historical and IPCC Weather/Climate data for future scenario projection (from 2019 to 2050)
- Airport thermal dynamic simulation and modelling based on CAD geometry.
- Airport PV power plant simulation based on a PV irradiance modeling python script.

Calibration and first simulation model adjustments:

- Analysis of the first simulation results
- Adjusting the hypothesis based on the results and consumption data.
- PV model simulation for the year 2019

Scenarios simulation – Energy conservation measures and PV projection in future milestone years based on thermal simulation and IPCC scenarios.

- Natural ventilation potential for the airport building, quantification and results.
- Windows solar shading impact and quantification.
- Cooling temperature setpoint increase sensitivity and results relative to the building consumption.
- PV Projection in future scenarios based on IPCC weather projection and TDS of the airport building projected consumption.

8.4.2.2 Models and other tooling

<u>IES VE 2023 modelling (Apache Thermal Calculator and Simulation tool)</u>

The building energy consumption is calculated using dynamic thermal simulation. The dynamic approach to calculation accepts the building as a "living" object, reactive to external elements, and considers the response of materials to variations in internal (occupants, equipment, etc.) and external (sun, wind, etc.) thermal loads. In contrast, a static simulation considers the building as an inert object, a simple addition of materials. Static calculations, for instance, calculate theoretical solar gains, but are unable to determine at what level and how the building is able to make the most of them.

In a dynamic thermal simulation, thermo-aerodynamic phenomena are dealt with only at the macroscopic level, between rooms and/or between a room and its environment, but have the advantage of being carried out in a dynamic regime, with variable boundary conditions. The air temperatures calculated are the average temperatures of the air volumes contained in the rooms, without considering vertical and horizontal gradients, unlike CFD studies. For the latter, thermal and aeraulic phenomena are treated microscopically, in steady-state conditions, enabling us to determine temperature, pressure, velocity, etc. at any point in the room.

In such a study, the building's thermal behavior is simulated throughout the year according to the building's local interactions with its environment, with meteorological data taken into account via a weather file.

Numerous other parameters, such as occupancy, temperature set points, ventilation rates, opening of windows and internal contributions from equipment (office equipment, lighting, etc.) are also taken into account in the calculation.

These parameters are detailed in the following paragraphs.

The multi-zone dynamic thermal software IES Virtual Environment version 2023 was used for this Energy Simulation. This tool is used to create a 3D building volumetry, define material properties, define internal inputs (equipment + occupants) and operating habits, in order to obtain refined building requirements.

The following modules were used in this study:

- ModelIT: Geometric modeling,
- Suncast: Dynamic shading calculation,
- ApacheSim: Dynamic thermal simulation,
- MacroFLo: Modeling air flows between indoor and outdoor spaces
- VistaPro: Detailed analysis of results by zone and for each component of the energy system.

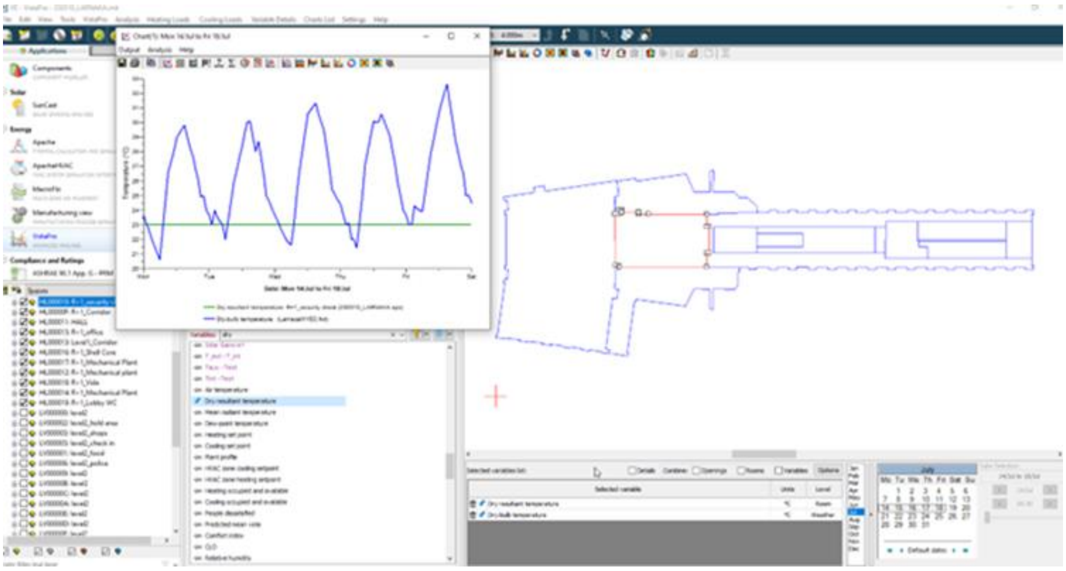


Figure 45, Exports from the dynamic thermal simulation model used.

IES is a dynamic thermal simulation software package with numerous applications in the field of High Environmental Quality. It can be used to analyze a building's behavior, component by component over time.

Modelling is, by its very nature, an attempt to translate real, variable and sometimes imperfectly understood situations into figures. A building's energy consumption is certainly impacted by its technical installations, but it is also highly dependent on usage, users and the weather. What's more, the thermodynamic laws of consumption efficiency are not always linear. As a result, thermal simulations and results are subject to theoretical limitations. Finally, since the models are based on fixed, homogeneous parameters, it is difficult to take account of the specific faults that can be found in a building. Sensitivity tests show that values should be read with a confidence interval of ± 15%.

Python PV irradiance modeling script

The PV study is based on the calculation of the incident irradiance on a given surface on the ground and on the calculation of the potential to exploit the incident and diffuse rays to produce electricity, directly exploited by the airport building. This method should enable a direct comparison to be made between the energy produced by photovoltaic panels and the hourly load curve obtained from the dynamic thermal simulation. In this way, the future scenarios derived from the TDS will be easily compared with the PV simulation, as shown by the following overview.

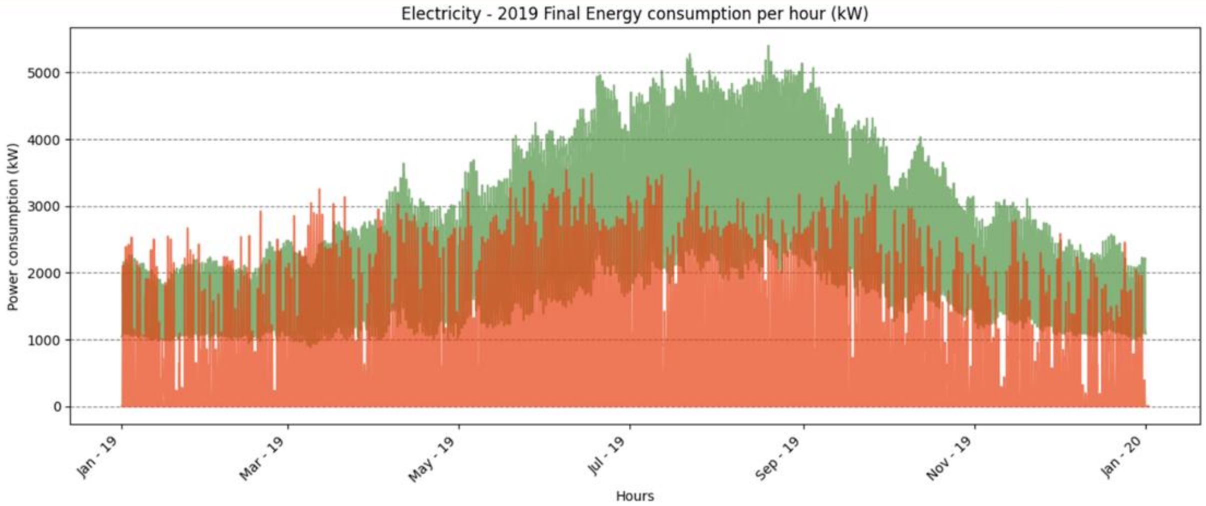


Figure 46, Comparison of the energy produced by the PV park and the hourly load obtained from the dynamic thermal simulation (On the x-axis, the time-one year, and on the y-axis the energy in kWh).

The chosen method corresponding to these criteria is a Python implementation of the methodology described in *Measurement and modeling of diffuse irradiance masking on tilted planes for solar engineering applications, Daniel Tschopp, Adam R. Jensen, Janne Dragsted, Philip Ohnewein, Simon Furbo,* (*https://doi.org/10.1016/j.solener.2021.10.083*) as this method allows the implementation of both direct and diffuse solar irradiance considerations.

This study examines the impact of obstructed views on diffuse irradiance distribution within fixed-tilt arrays, crucial for accurately designing and predicting power output in photovoltaic and solar thermal projects. It fills a research gap by analyzing how surrounding rows affect sky and ground visibility. High precision pyranometers were positioned in an experimental array with various row spacings and tilt angles.

A new model was developed to estimate diffuse tilted irradiance, considering obstructed views. Validation showed the model accurately represents diffuse irradiance distribution. Results reveal significant reductions in diffuse irradiance at lower collector sections, especially with narrow row spacings and steep tilt angles. For example, in the most extreme scenario, diffuse irradiance decreased by 64% at the bottom and 89% on average relative to the top, highlighting potential biases in performance assessments relying solely on top measurements. Utilizing the

"*Measurement and modeling of diffuse irradiance masking on tilted planes for solar engineering applications"* model is highly relevant for digital simulations of PV production in terms of:

- Irradiance prediction accuracy: The model accounts for obstructed views in fixed-tilt arrays, providing more precise estimates of diffuse irradiance. The context of this study, accurate irradiance prediction is crucial for assessing the performance of PV systems and the quantification of production.

- Performance evaluation: By considering the impact of view obstructions, the model enables more realistic evaluations of PV system performance. A simulation using this model can offer insights into how different configurations, such as row spacings and tilt angles, affect energy generation, considering a shadow ratio, allowing a better-informed decision-making in the perspective of representing real-world conditions, such as shading effects from surrounding rows.

- Projection accuracy: Accurate simulation models contribute to reliable projection of PV system output. By incorporating the thermal dynamic simulation results, along with IPCC scenario weather at an hourly scale, the accuracy of energy production will greatly be improved, aiding in storage integration and energy planning.

- Risk and uncertainty reduction: Utilizing such a complete model in digital simulations helps mitigate risks associated with PV system implementation. By providing more accurate predictions, simulations can help avoid modeling flaws or bad representation issues, ultimately reducing project risks and uncertainties.

8.4.2.3 Process, timeline and milestones

A Dynamic thermal simulation of both the current and future state of the airport building is studied with projections for the milestone years 2030, 2040 and 2050. Concerning the reference site state, the modeling is based on HVAC report data and historical weather data (2019) compared to measured temperature on site. Future states of the airport building are then projected on the model, considering the hypothesis on the evolution of the building in terms of passengers' staff evolution, and also on IPCC climate scenarios for the milestone years. The chosen IPPC scenario in the case of this study is the IPCC RCP2.6, which is the most optimistic scenario projection, as observed on the following graph.

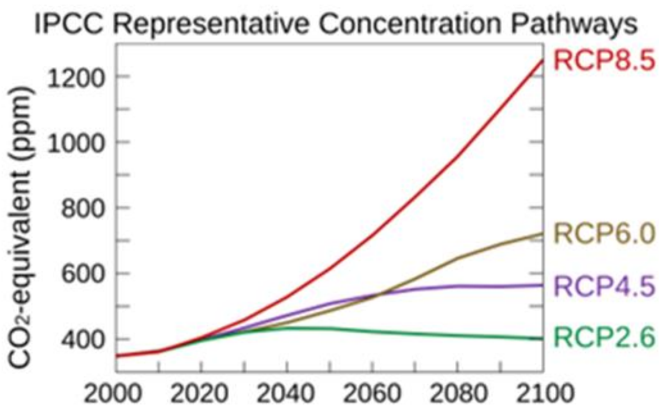


Figure 47, IPCC Representative Concentration Pathways

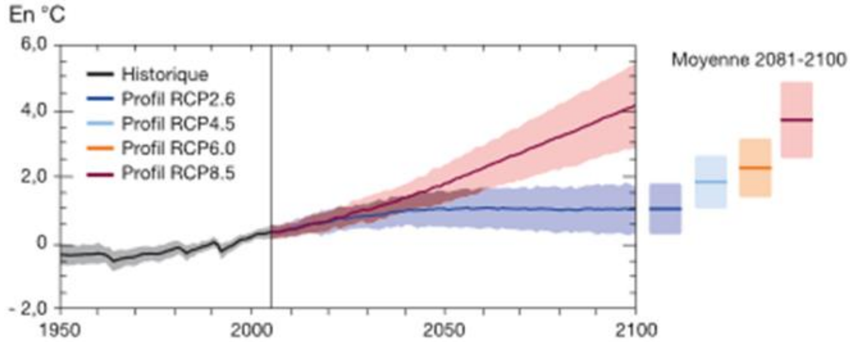


Figure 48, IPCC Climate Scenarios (°C)

The scenario projection limits emission such that global temperature change is contained between 0.9°C and 2.3°C rise, according to IPCC. The corresponding weather files for the milestone years show a shifting temperature distribution towards hotter temperatures as shown by the following graph.

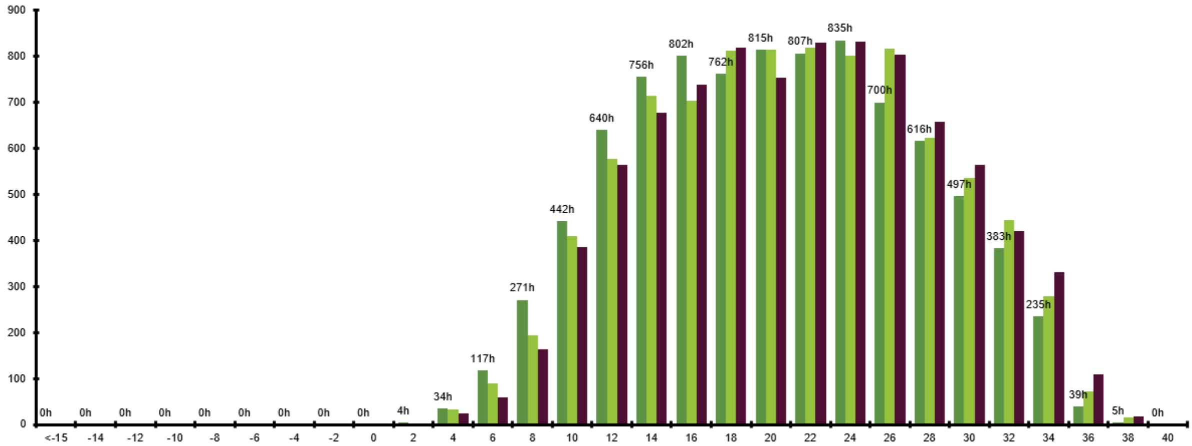


Figure 49, Temperature distribution for the scenario used in the simulation. X-axis, temperature, Y-axis, number of hour in year

The results of the simulation will consider the shift in terms of temperatures and the impact on the airport building consumption along with the increase in passenger and staff.

8.4.3 Scenarios and Solution pathways

8.4.3.1 Introduction to the airport energy system

Cyprus energy mix is based mainly on burning of fossil fuels, thus resulting to very high emission factors. The combination of the energy mix and the isolation of the electricity grid and the lack of interconnections with other systems results to an electricity grid with very limited flexibility and specific capacities for introduction of renewable energy systems. Considering the high fuel cost of the last few years, along with the greenhouse gas taxes/cost on the electricity price makes the improvement of energy efficiency and the introduction of renewable energies for self-production a very beneficial combination.

Larnaka Airport is connected on the island's high voltage electricity grid and operates a private medium voltage grid for meeting the electricity demand of the various airport's activities.

Following the successful implementation of many energy conservation projects throughout the last decade, Larnaka Airport reduced its energy consumption by more than 35%, reaching a stage in which the energy consumption remains relatively stable. The graph below presents the reduction of energy usage combined with the significant increase in passenger traffic since 2010.

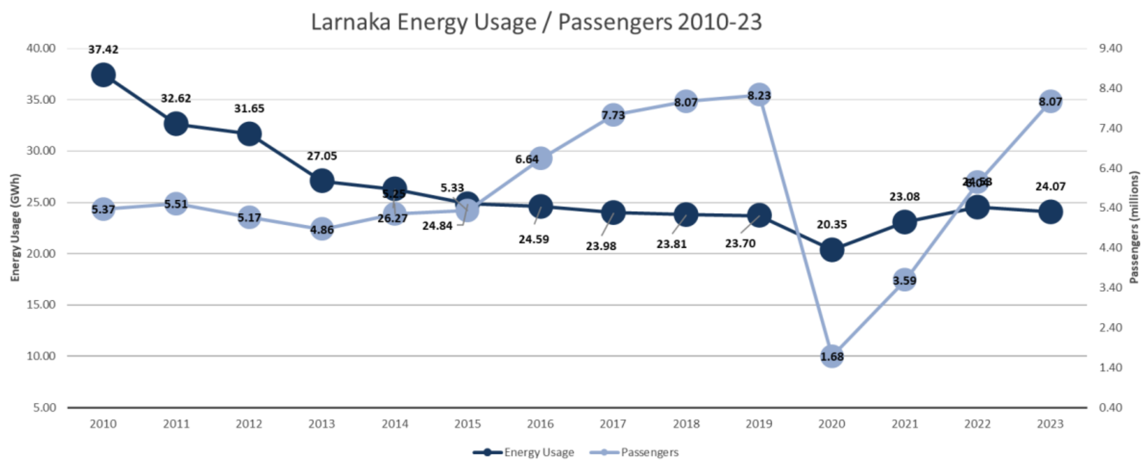


Figure 50, Larnaca Energy Usage and Passengers 2010-2023

In order to understand the details of the energy system and be able to identify the most significant energy usages, Larnaka Airport through a system of more than one thousand power analysers identified the various consumptions, introduced key performance indicators to monitor and set specific short, medium and long term targets.

The most significant energy usages are presented in the graph below.

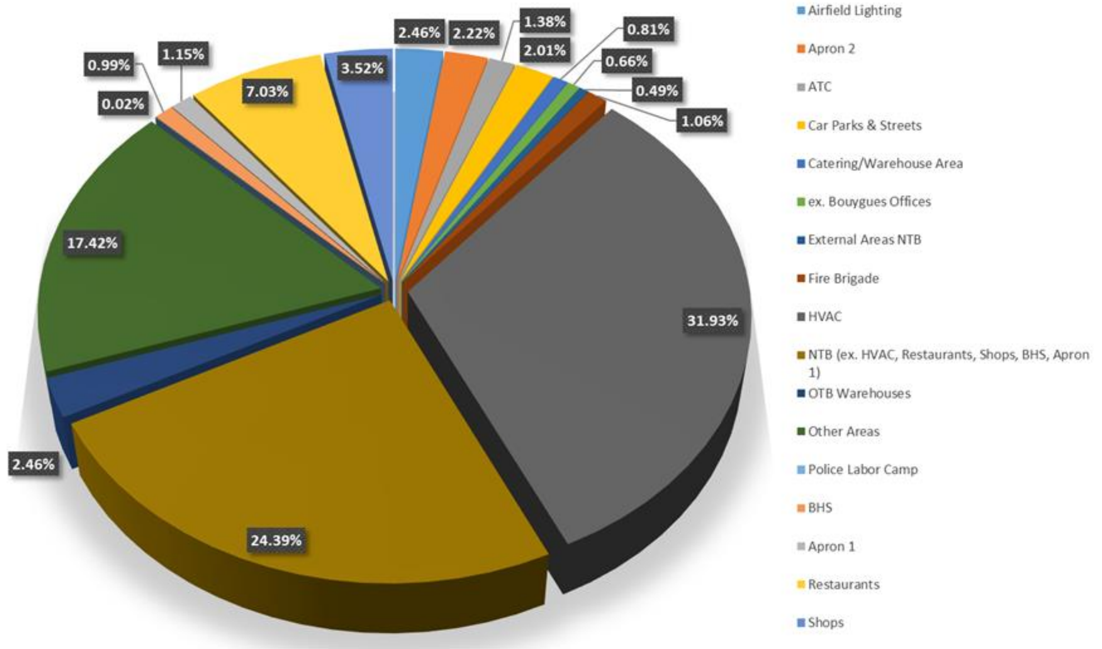


Figure 51, The most significant energy usages

The majority of the directly controlled carbon dioxide emissions of Larnaka Airport are related to the electricity consumption. The installation of an on-site photovoltaic plant contributed towards the reduction of those emissions. A series of actions and initiatives have been considered and added to the long term plan and roadmap, in order to set specific medium and long term targets. The two main milestones are the Net-Zero target of 2050 and the aim for reducing all Scope 1 and 2 emissions by 96% by 2030 compared to 2010.

For this reason the targets of emissions and electricity per passenger and per square meter of buildings are introduced to monitor the progress towards the two main targets described above Additional milestone years have been considered during the various scenarios analysisEnergy system scenarios

The energy system scenarios took into consideration the following parameters:

- Passenger and Staff evolution graph
- PV evolution (from 3.5 MWp to 4.7 MWp by 2030)
- IPCC - RCP 2.6 choice justification
- Ventilation optimization (2019) 25m3/h
- Light optimization (LED + dimming)
- Temperature optimization : 24/25 °C

Other technological solutions considered amongst others are the enhancement of the existing photovoltaic plants at Larnaka Airport and the introduction of energy storage solutions, the electrification of the fleet and the ground support equipment, the modification of conventional fuel burning ground power units generators to electric ground power units and variations in the commuting. These scenarios are not studied in this report.

8.4.4 Modelling Framework Implementation

8.4.4.1 Modelling framework description

- Initial state of airport building modeling for Thermal Dynamic simulation (TDS):

Geometric representation:

The modelling of the airport begins with the creation of the geometry, based on the given airport 2D plans to create volumes on IES VE using the ModelIT Tool. Glazed surfaces are also modelled. An accurate geometric representation of the airport is essential for assessing its energy consumption, according to each specific volume and use. The result of the geometric work in axonometric view and 3D view is shown below.

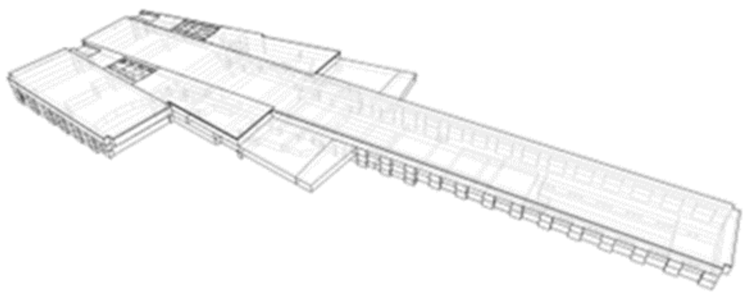


Figure 52, Geometry of Larnaka Airport used in the dynamic simulation

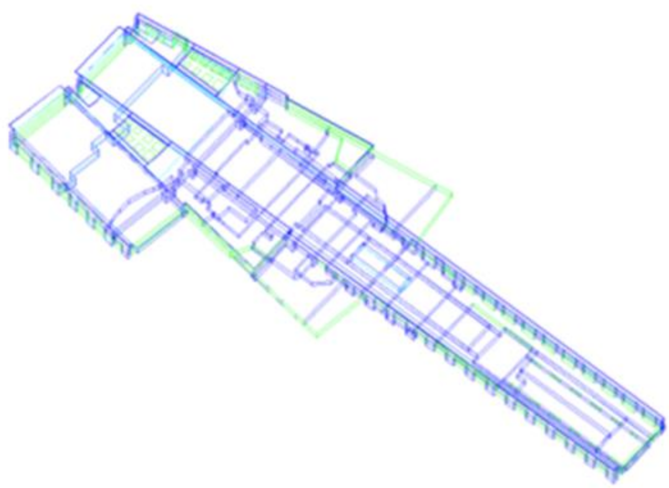


Figure 53, Assigning each surface group a material typology for the purpose of the simulation.

Constructions and surface groups:

Each surface group is assigned a material typology, based on the assumptions exchanged with the airport, in an attempt to best represent the reality of the building. The simulation is based on the following assumptions about the building envelope:

Type	Description	U value (W/m²K)	R insulation
Roof - concrete	Concrete 250 mm + external insulation	0,31	3
Roof - metal	Steel – 0,6mm	7	-
Facade - concrete	Concrete 400 mm	2,2	-
Facade - metal	Metallic cladding + insulation	0,45	2
Floor - internal	Concrete 150mm	3,6	-
Floor - underground	Concrete 150mm	3,6	-

Figure 54, Assumption so of the U values of the building envelop used in the simulation

Zoning:

Zoning is crucial within the model's framework, with a primary focus on delineating core functional areas such as offices in commercial buildings or residential living spaces. However, it's also vital to account for the size and volume of miscellaneous ancillary spaces like elevator shafts, bathrooms, and staircases. This step refers to the geometric representation of surface areas and volumes.

Instead of individually modeling each space, the approach involves outlining zones that encompass all spaces of a similar type. This zoning step focuses on finding the right balance. An excessive number of zones can lead to unnecessary complexity, while too few may sacrifice detail.

Thermal template:

This step assigns building thermal template information to the proposed zoning model based on the selected thermal template scheme. This step is closely linked to the previous "room/zone group assignment" step. Therefore, all spaces in the model must first be assigned to the appropriate groups. This can be done manually or with tools provided in the previous step. This step essential performs a global assignment of thermal templates. We consider several distinct thermal zones, all of which have properties associated with their use:

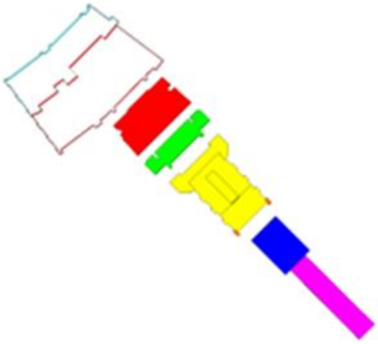


Figure 55, Zoning of the Terminal used in the simulation – Level 0

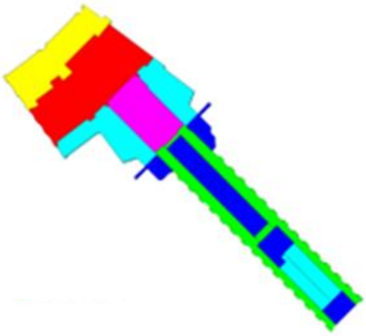


Figure 56, Thermal templated used in the simulation – Level 1

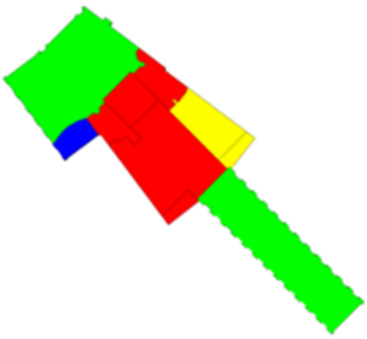


Figure 57, Zoning of the Terminal used in the simulation – Level 2

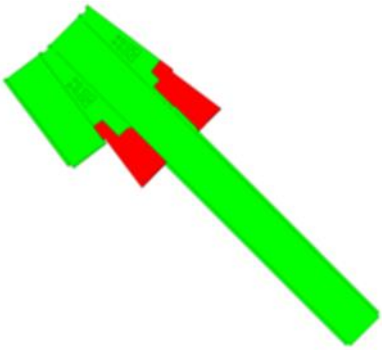


Figure 58, Thermal templated used in the simulation – Level 3

The main thermal templates modelled above are as follows:

- Baggage claim
- Bus arrivals
- Check in - departure
- Mechanical Plant
- Meetings greetings
- Office
- Restaurants
- Security emigration
- Shops

Each thermal template is assigned parameters, usage schedules, operational profiles corresponding to:

- Ventilation, infiltration and HVAC systems
- Heating profile
- Cooling profile
- Internal gains (occupation, electric equipment, lighting)

To separate the two main dynamics of airport occupancy in terms of passengers, the daily occupancy schedules have been divided into two categories. It is assumed that the airport receives twice as many passengers in summer as in winter. Thus, two separates occupancy profiles are applied throughout the simulation year.

Thermal Dynamic simulation and calibration

We have been provided with historical consumption data for 2019. These are high quality data on a monthly scale, making it possible to observe the evolution of energy consumption in direct relation to Larnaka historic climatic condition. This historical consumption data can be seen in the following figure.

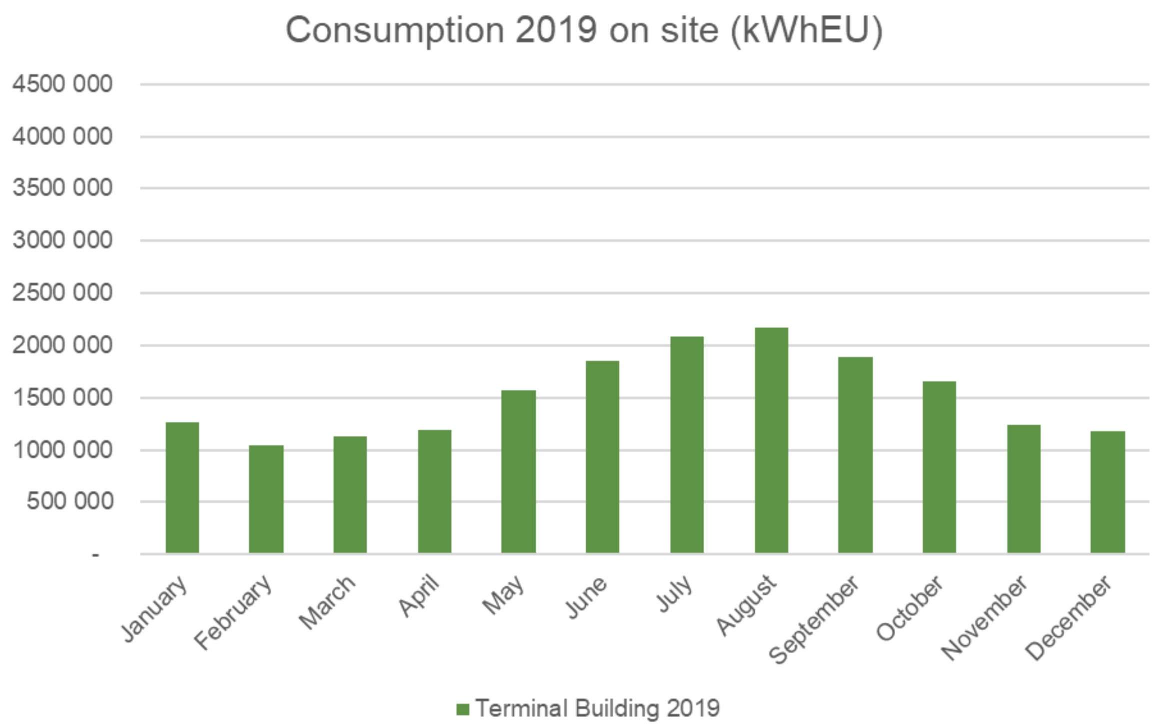


Figure 59, Historical consumption data

Here we can see that summer temperatures have a strong impact on consumption. This suggests that air-conditioning consumption is in the majority. This is consistent with the historical climate data for Larnaka.

In the following graph, temperatures measured by the airport during 2021 can be observed. Summer temperatures are very high on average, with maximum recorded temperatures of around 38°C. Winter temperatures are milder on average but are still dominated by relatively high temperatures on a daily basis. No negative temperatures were recorded during the year. This suggests that heating use is low in winter.

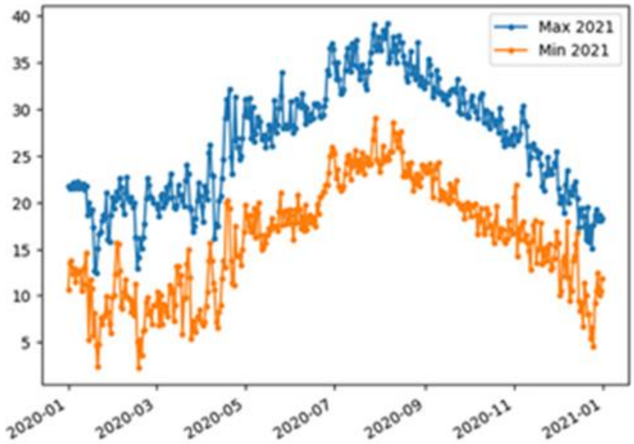


Figure 60, Temperatures recorded at Larnaka Airport in 2021

In order to produce a thermal model as close as possible to the reality of the airport building, the choice of weather data is crucial. The weather data collected for the simulation will be compared with the measurement data to observe any potential discrepancies.

The data used in the following simulations all come from *Meteonorm Software* a weather and irradiation data provider. Here is a comparison between the temperatures measured on site and the weather data used for the study and calibration of the model for 2019 coming from *Meteonorm Software*.

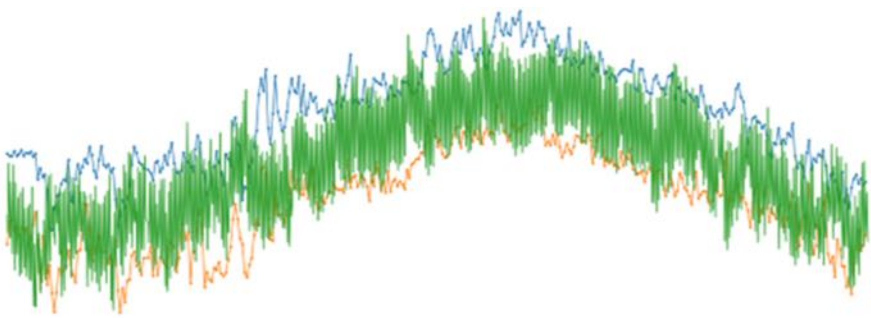


Figure 61, weather data used for the study and calibration of the model.

It can be seen that the temperatures used to produce the model are mostly within the maximum and minimum ranges of the data recorded on site. Some deviations can be observed, particularly during winter, when the simulation temperatures seem to correspond to cooler weather. These reasonable deviations may be caused by annual temperature variability between 2019 and 2021. The data measured on site tends to validate the historical *Meteonorm Software* data used for the simulation, so the deviations are considered to be acceptable. The weather data can then be used to simulate the dynamics of the airport building in 2019, based on the simulation assumptions described above, in particular for the calibration stage.

The calibration stage is required when several input parameters of a model are uncertain, such as the average occupancy of a site or the average efficiency of HVAC system. In such regular cases, the output of the model, for example cooling consumption is uncertain.

The calibration process therefore consists of defining the uncertainties we have about the parameters, and then updating these uncertainties, generally by reducing them, by observing the consumption of the building or buildings being modelled.

Quite intuitively, calibration cannot reduce the uncertainty of an input parameter if its influence on consumption is not sufficiently significant. Thus, the most influential parameters are selected before calibration, and only these parameters are calibrated.

Thus, adjusting the simulation parameters on IES VE such as occupancy, lighting or temperature setpoint, with respect to the initial hypothesis and given technical data, the distribution of consumption appears as follows:

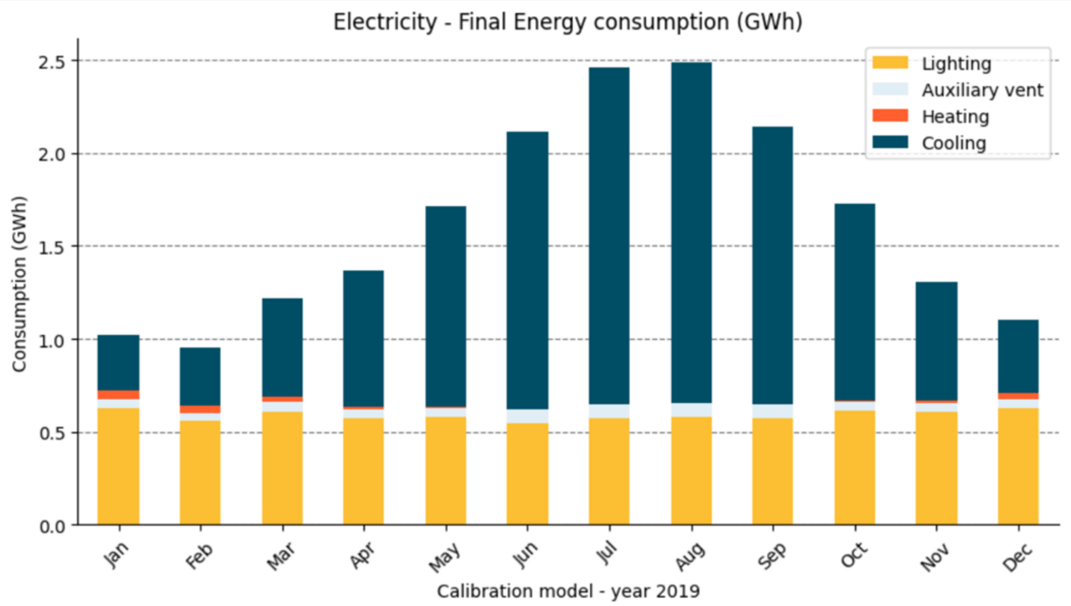


Figure 62, Distribution of Electricity Energy Consumption as modelled.

We find a profile with high monthly variability and a distribution of consumption strongly dominated by air conditioning. A more detailed breakdown of consumption can be represented as the following:

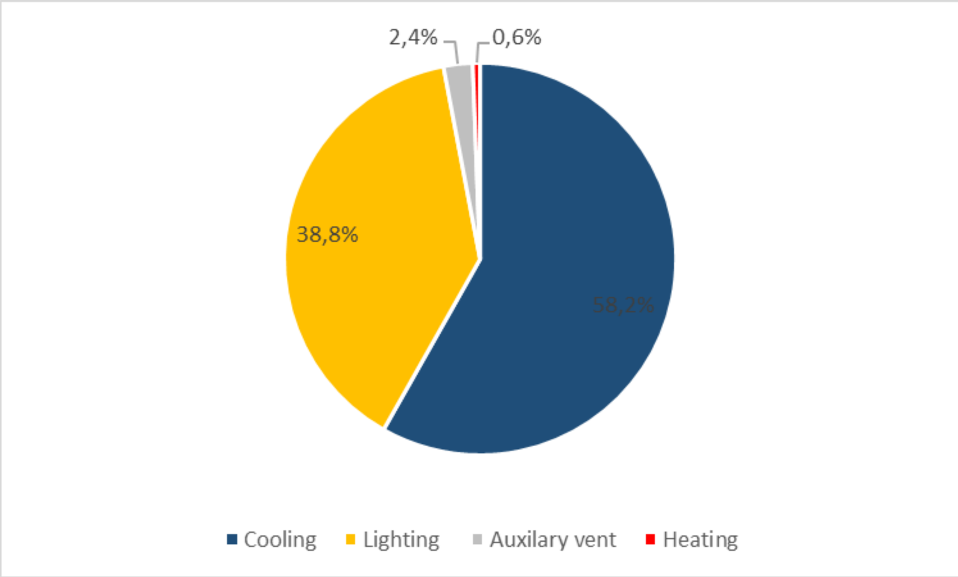


Figure 63, Electricity Energy Consumption

Several points emerge from this distribution:

- The building's total energy consumption is largely dominated by air conditioning, as expected. This is due primarily to the high temperatures throughout the year, the significant solar gain, but also to the important share of internal gains inside the airport building, shared between passengers, staff, electrical equipment and the radiant part of the lighting. The second area of consumption is lighting, which is mostly always on (day and night) in all zones. Only the offices have a lighting cycle that is interrupted at night.
- With a high proportion of internal gains due to passengers, electrical equipment and lighting, along with solar gain, heating represents the lowest proportion of consumption.

Direct comparison between simulation results and historical data

This distribution of consumption, derived from the thermal simulation, attempts to approximate the reality of the building based on assumptions and past consumption data. A direct comparison between historical data and consumption data reveals an annual difference of less than 5%.

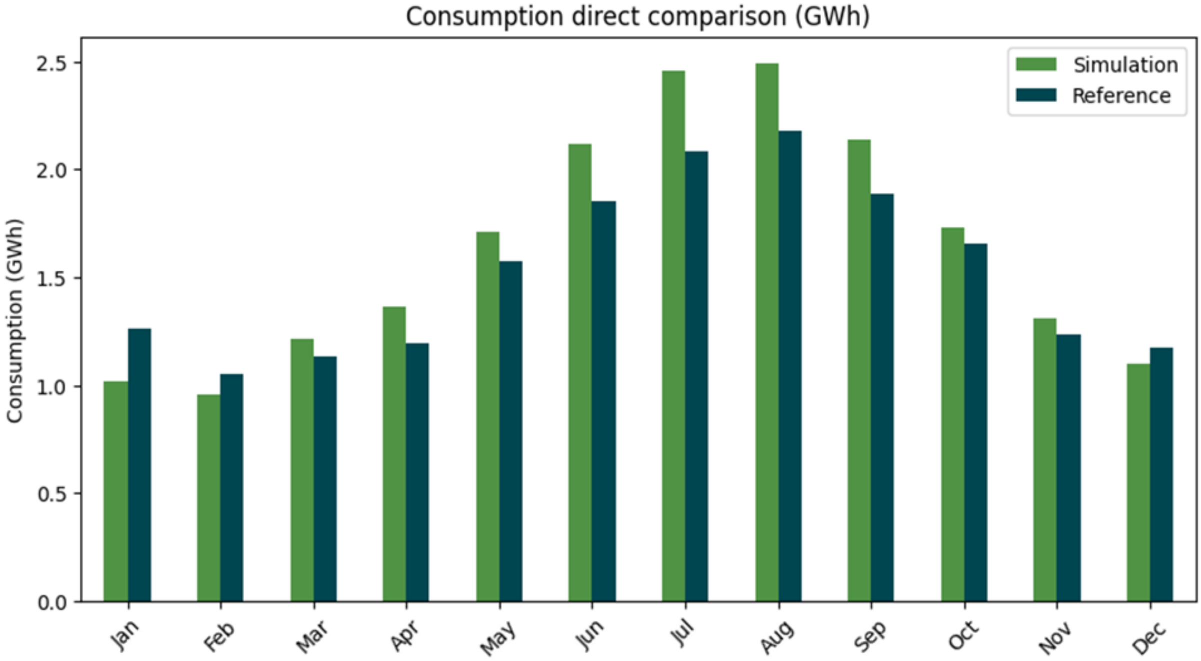


Figure 64, Electricity Energy Consumption simulation versus reference

As seen on the previous graphs, the monthly profile matches. The electricity consumption relative gap between simulation and historical data is 4.7%. This is a reasonable gap, since input data is monthly data without usage decomposition. This means that the model can be considered calibrated. Obtaining a calibrated model ensures reliable results for impact studies of energy conservation measures and future projections.

- Hourly load curve

Now reliable, the model can be used to obtain an hourly load curve from the simulation, enabling a PV study to be carried out.

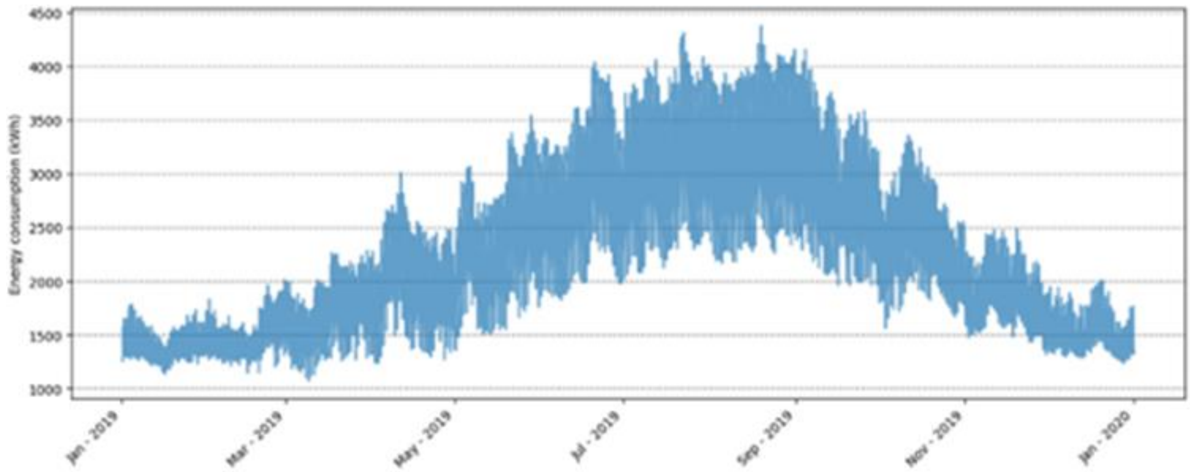


Figure 65, Simulation of PV (solar) production. Annual evolution of the production in kWh.

- PV simulation

For the simulation the airport was assumed to have a photovoltaic system already in operation since 2019. The primary objective of PV simulation is to model the site's actual photovoltaic production based on weather data and to represent a realistic proportion of actual production. This first stage aims to validate the PV model and ensure the relevance of results for projected scenarios based on future load curves and IPPC weather data.

The simulated PV production will be compared with the load curve previously obtained for 2019. For 2019, the aim is to obtain a result close to the current PV capacity, i.e. a production of 3.5 MWp for 6 million kWh produced annually.

Finding a similar result will validate the use of the model. This step is similar to the previous calibration phase of the thermal simulation. The assumptions of the PV model are as follows:

- We consider a PV surface area equivalent to 3.5MWp of production.
- The efficiency ratio of the PV panels modelled is set at 20%.
- PV modules are South oriented.
- The slope of the PV modules is set at 20° to avoid sun glare on landing planes.
- Solar azimuth represented as a time series from Meteonorm solar angle data for Larnaka in 2019 (°deg).
- Solar altitude represented as a time series from Meteonorm solar angle data for Larnaka in 2019 (°deg).
- Estimated local earth albedo.

These values are then used to calculate the following quantities required for the simulation method:

- BNI: (Beam) Direct normal irradiation - time series (W/m²)
- DHI: Diffuse horizontal irradiance - time series (W/m²)
- GHI: Global horizontal irradiance - time series (W/m²)

As stated, most of the solar parameters are taken from weather files, which are determined beforehand on the basis of the previous assumptions. The PV simulation gives the following production potential for the year 2019:

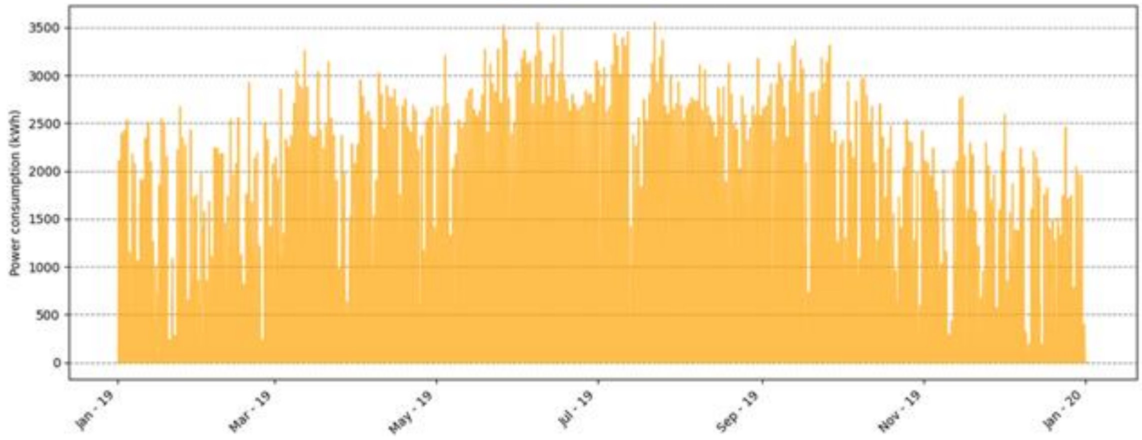


Figure 66, Simulation of the PV (solar) energy produced in 2019.

By overlaying the data simulated during the previous TDS, it is possible to determine the proportion consumed and the proportion requiring storage.

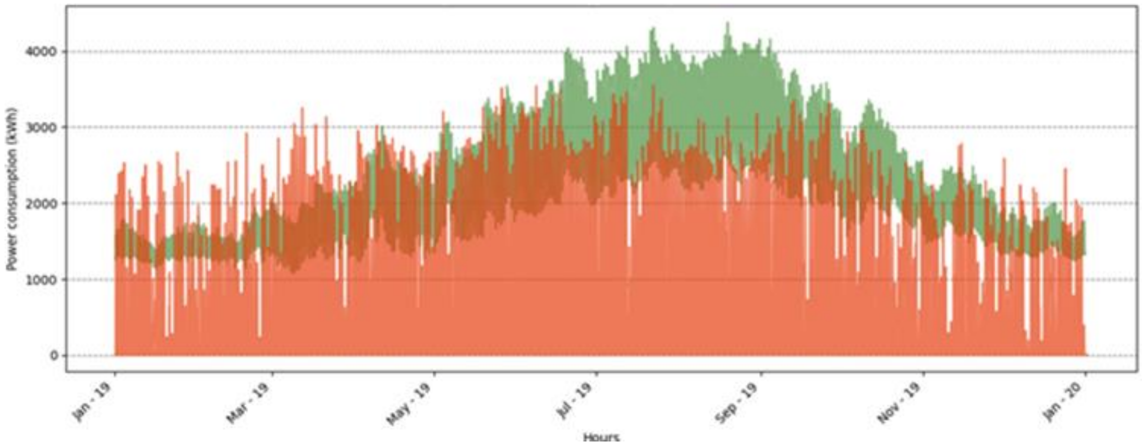


Figure 67, Proportion of the PV produced energy consumed and the portion requiring storage.

The Initial PV simulation results for 2019 are:

- Solar PV energy production for the year 2019: 5.96 GWh
- Elec energy consumption for the year 2019: 19.15 GWh
- Solar PV energy consumption coverage for the year 2019: 31.11%
- Self-consumption: 5.74 GWh (96.36%)
- Injected/Storage need: 0.22 GWh (3.64%)

These results reveal that the model is consistent with the reality of the current PV installation in terms of production and self-consumption. The results of future projections can then be approached with a high degree of confidence in the model. These initial results also show some interesting seasonal features, which are worth looking at in greater detail:

Over the winter period, and particularly in February, electricity power demand is exceeded by PV production. This implies a need for storage during these periods of surplus production. By comparing the self-consumption requirement with the PV power output, the storage need can clearly be identified, represented as gaps between the two curves:

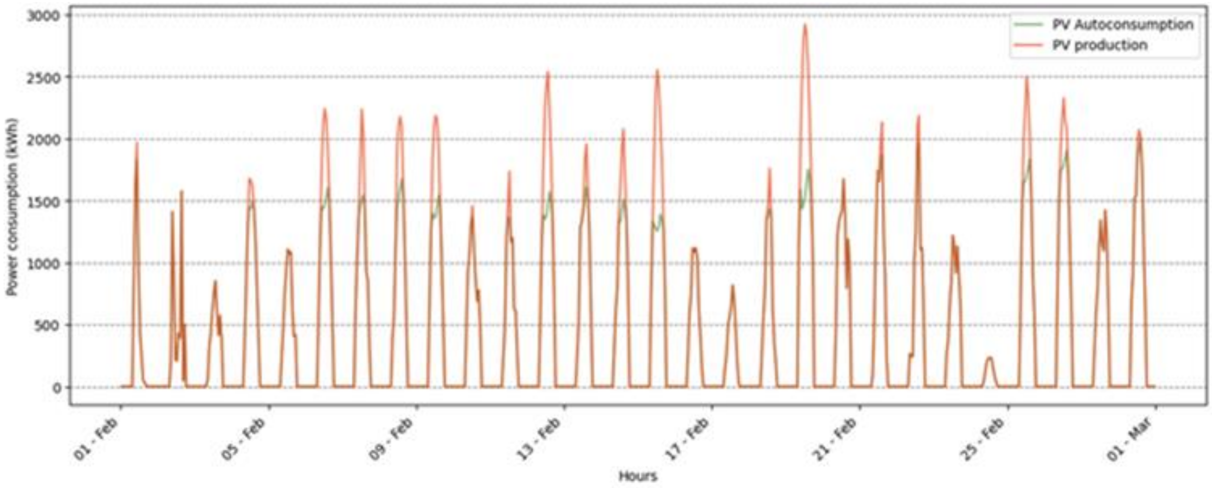


Figure 68, PV production vs Electricity Energy Consumption. The need for storage is the difference between the two graphs

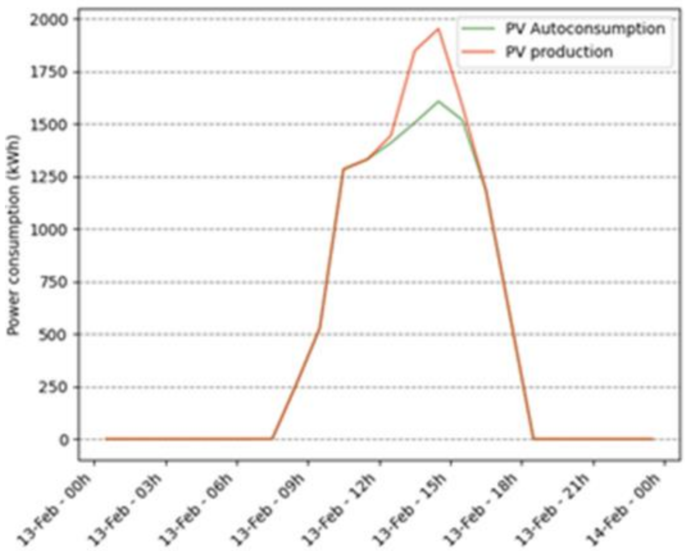


Figure 69, Single day PV production vs Electricity Energy Consumption

By focusing on a one-day period, it is possible to highlight the need to store the surplus produced. Conversely, summer periods are never overcompensated, as the following July sample illustrates

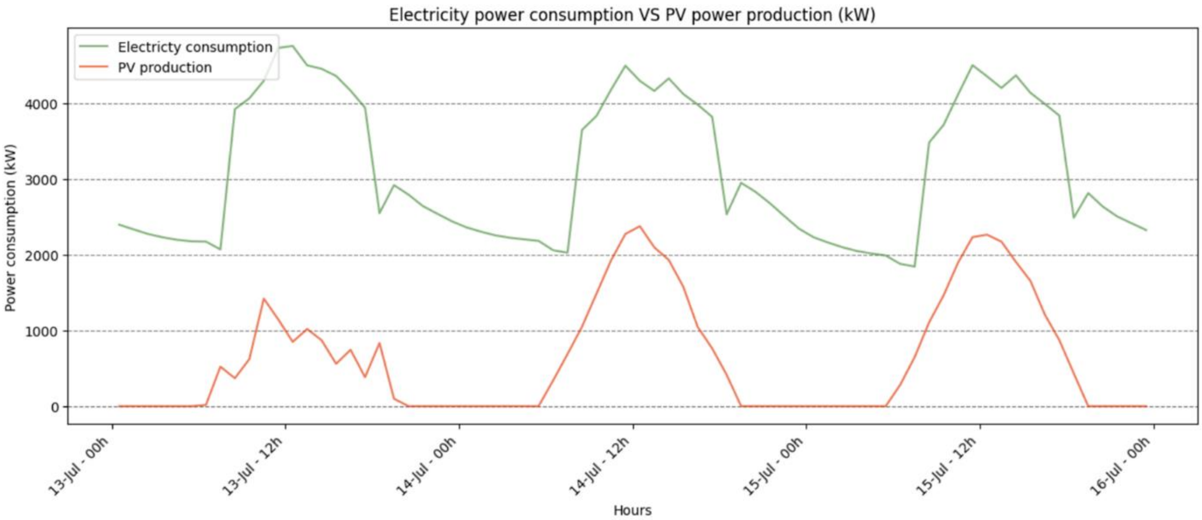


Figure 70, July Electricity Energy Consumption exceeds PV production.

In this way, it is possible to highlight the peak PV overproduction to be stored on an annual scale. Maximum production pic to store in 2019: 1475.9 kWh as simulated.

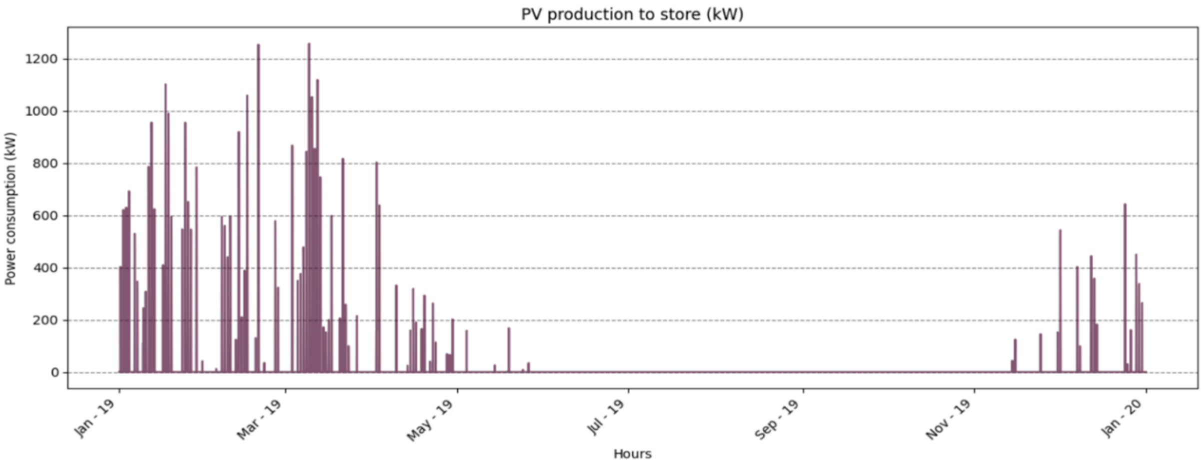


Figure 71, PV production to be stored in kWh

8.4.4.2 Airport energy system model implementation

Important note :

These results are exploratory in nature and consider the calibration assumptions previously established. Constraints linked to the airport environment, such as safety, comfort, structural limitations, emissions and noise pollution, are neglected here in favor of demonstrating the energy potential of these actions. The assumptions made are deliberately extended to maximum potential. From a practical perspective, these energy efficiency measures would require important adaptation.

Energy Conservation Measure (ECM) 1 – Natural ventilation potential

The first proposed energy conservation measure (ECM) seeks to highlight the energy gains possible through natural ventilation. There is great potential for natural ventilation when outside temperatures are below 25°C. The following figure shows that natural ventilation can contribute to the thermal unloading of the building from September to June when the outside temperature is potentially below 25°C.

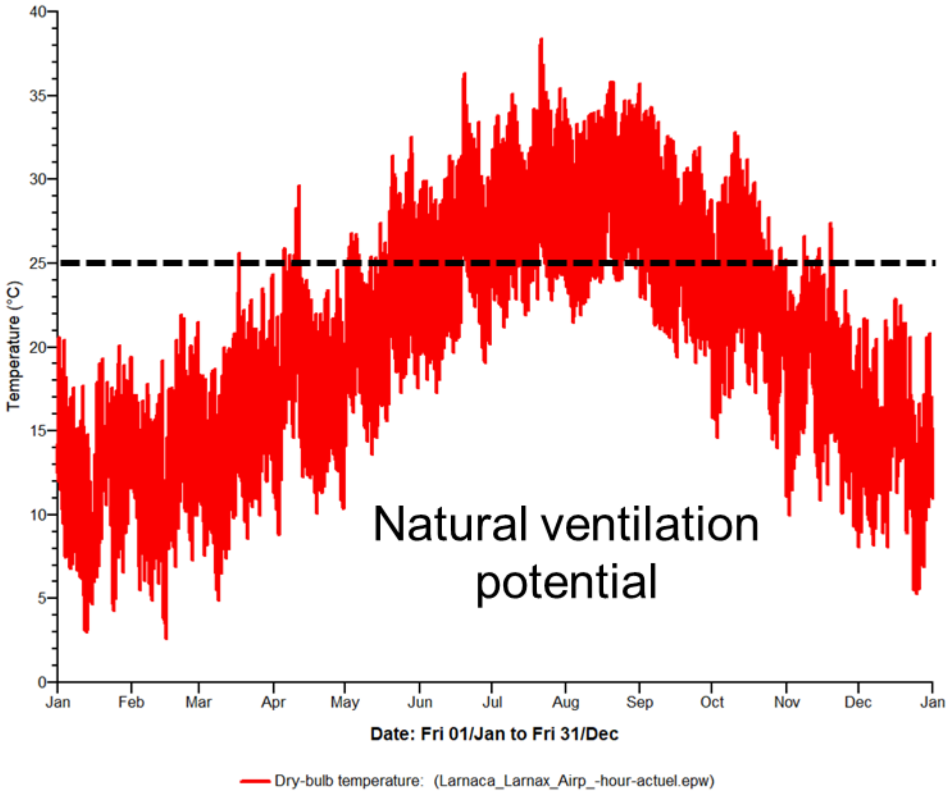


Figure 72, Natural Ventilation Potential

Harnessing natural ventilation offers several energy-related advantages. Natural ventilation utilizes natural forces such as wind and temperature differentials to provide air renewal without relying on mechanical systems. By avoiding the use of electric fans, the building's energy consumption is reduced, leading to long-term savings on energy bills.

Additionally, natural ventilation helps maintain a comfortable indoor temperature, below temperature cooling setpoint, by optimizing airflow to cool spaces throughout the year. As seen on previous graphs, there is a high potential for Larnaka airport.

The simulation of this ECM involves the following hypothesis:

- Louvres are applied to every glazed surface at a surface ratio of 30%
- The opening threshold triggers when Int. temperature is greater than Ext. temperature, if Int. temp is greater than 25°C and if Ext. temp greater than 20°C.
-

ECM 2 – Solar ext. window protection shading.

The second proposed energy conservation measure (ECM) seeks to highlight the energy gains possible through the installation of mobile solar shading systems. Installing solar shading systems on the airport building in a hot climate like Cyprus offers several energy-related advantages.

Solar shading helps reduce solar heat gain by blocking direct sunlight from entering the building, thereby decreasing the need for air conditioners. This results in lower energy consumption for cooling, leading to reduced electricity consumption and operational costs. Moreover, solar shading devices can enhance thermal comfort indoors by preventing excessive glare and maintaining more stable indoor temperatures, improving the comfort of occupants but also reducing the likelihood of overheating.

The simulation of this ECM involves the following hypothesis:

- Solar protection shading is applied to every glazed surface with a transmittance Tr = 0.2
- Original windows are kept.
- The solar shading triggers if the incident irradiation is greater than 300 W/m² on a glazed surface.

ECM 3 - Cooling temperature setpoint increase.

Increasing the setpoint temperature of a cooled building by just one degree in a hot climate like Cyprus can yield several energy-related advantages. Raising the temperature setpoint reduces the workload on the air conditioning system, leading to lower energy consumption. Even a minor adjustment in temperature can result in significant energy savings over time, especially in hot regions like Cyprus where cooling demands are high throughout the year. In such a case, comfort is greatly link to humidity,

The simulation of this ECM involves the following hypothesis:

- Cooling setpoint increase in each cooled area by 1°C.
- Global 27°C setpoint

Presentation of modelling results

This part will be shared between the different result points obtained from the above modelling framework, i.e.:

- ECM results
- PV results
- Global recap and projections based on results.

ECM 1 – Natural ventilation potential

The simulated results are the following:

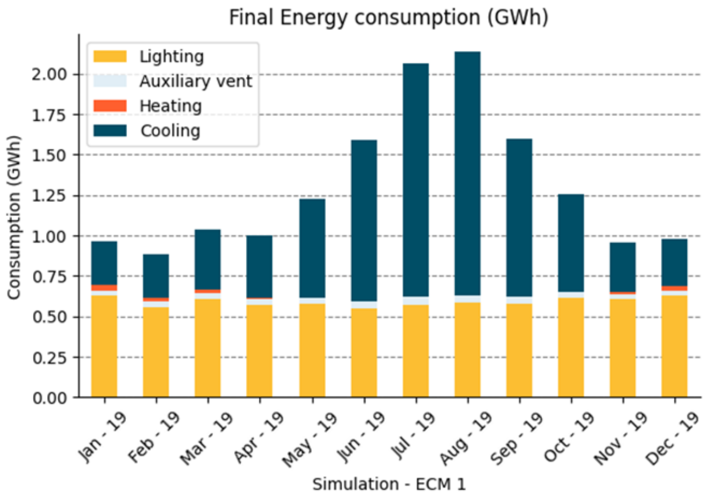


Figure 73, ECM 1 consumption profile. Simulation of natural ventilation potential

The direct impact of such measures is a global estimated gain of 20% and the following remarques can be formulated.

- Mid-season periods benefit greatly from natural ventilation.
- Energy savings make monthly variations in consumption less obvious, which is an advantage. Consumption is smoother throughout the year.
- Net gains can also be observed in the summer season, with a visible gain compared to the model calibrated above, although consumption remains dominated by air conditioning during the summer.

This is a highly relevant ECM offering major gains in optimal conditions as simulated. The study shows great potential for natural ventilation. It seems worthwhile exploiting this avenue to reduce the airport's energy consumption and carbon emissions.

ECM 2 – Solar ext. window protection shading

The simulated results are the following:

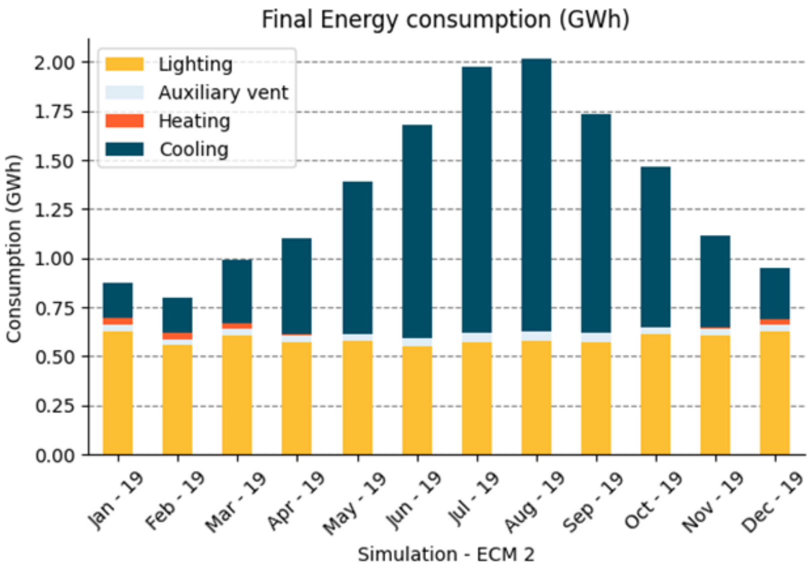


Figure 74, ECM 2 consumption profile. Simulation of Window Protection Shading

The direct impact of such measures is a global estimated gain of 17% and the following remarques can be formulated:

- Air conditioning usage decreased throughout the year.
- A slight increase in total lighting consumption is due to the light compensation required when the solar shading devices are switched on.

This is another highly relevant ECM, offering major gains in optimal conditions as simulated. This study shows great potential for the installation of solar protection systems. It would seem worthwhile exploiting this avenue to reduce the airport's energy consumption and carbon emissions.

ECM 3 - Cooling temperature setpoint increase.

The simulated results are the following:

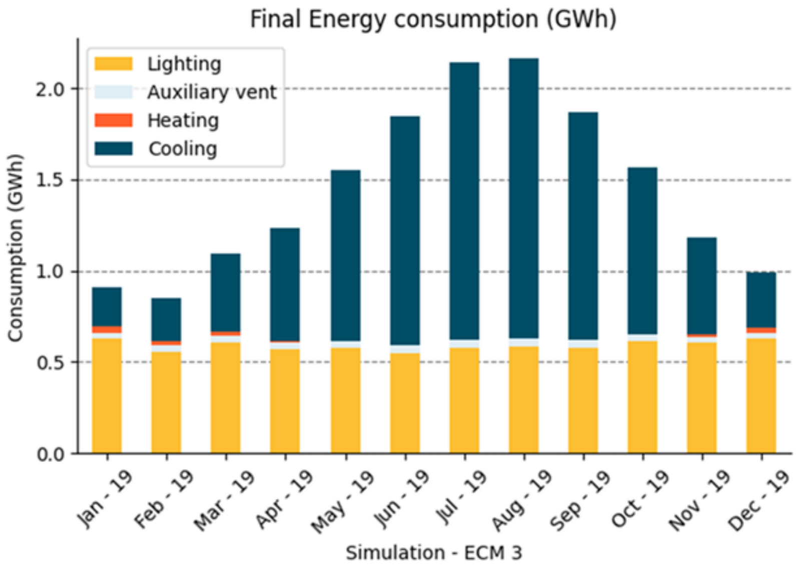


Figure 75, ECM 3 consumption profile. Simulation of temperature Setpoint Increase

The direct impact of such measures is a global estimated gain of 11% and the following remarques can be formulated:

- The cooling profile remains identical to the calibration model, as expected, but there is an overall reduction in consumption, and a lower proportion of air-conditioning.

This is an ECM that highlights the significant impact of reducing air conditioning by just one degree on the airport's energy consumption. This action can be coupled with the previous one for a result with greater acceptability and comfort for users and staff.

PV projection

The PV simulation results for the future milestones years, compared to the relative airport consumption evolution, are represented as follows:

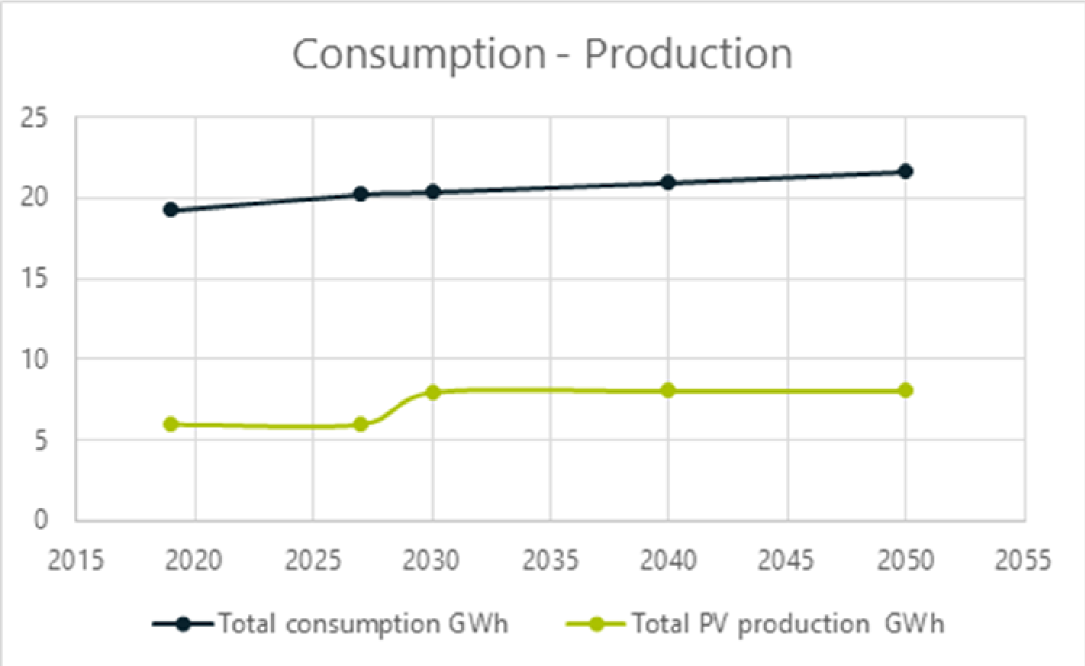


Figure 76, PV production Simulation Results for future milestone years.

The airport's projected consumption is mainly influenced by the increase in passenger and staff numbers, as well as on the increase in air-conditioning requirements in response to the average rise in temperatures between 2019 and 2050, according to the IPCC's prospective meteorological data.

Increased PV production is a response to this rise in consumption from 2030 onwards. It is estimated that average annual PV production will be around 8GWh in 2030, according to the simulation method used in this study.

As seen above, the proportion of self-consumption in winter decreases, as a result of lower air-conditioning requirements. The increase in PV production leads to a reduction in the building's self-consumption capacity. This quantified phenomenon can be seen in the figure below.

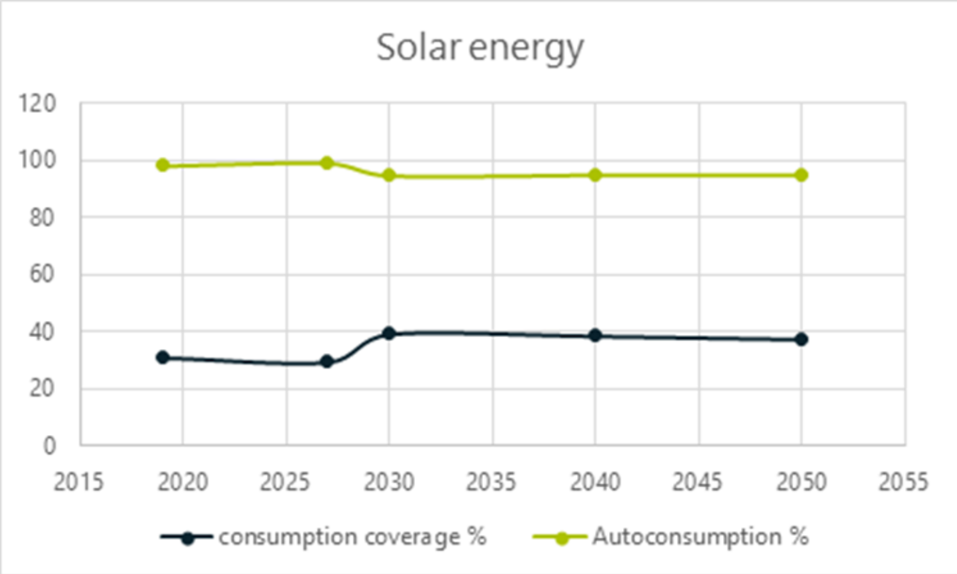


Figure 77, PV production and consumption for future milestone years

There is thus a direct link between increased PV production and reduced self-consumption. However, the increase in PV production leads to an increase in consumption coverage, as expected.

After 2030, these two phenomena tend to diminish over time, as air-conditioning needs and overall building consumption increase. The direct impact on storage capacity needs can be observed below and includes the evolution of storage in comparison with the maximum instantaneous power to be stored.

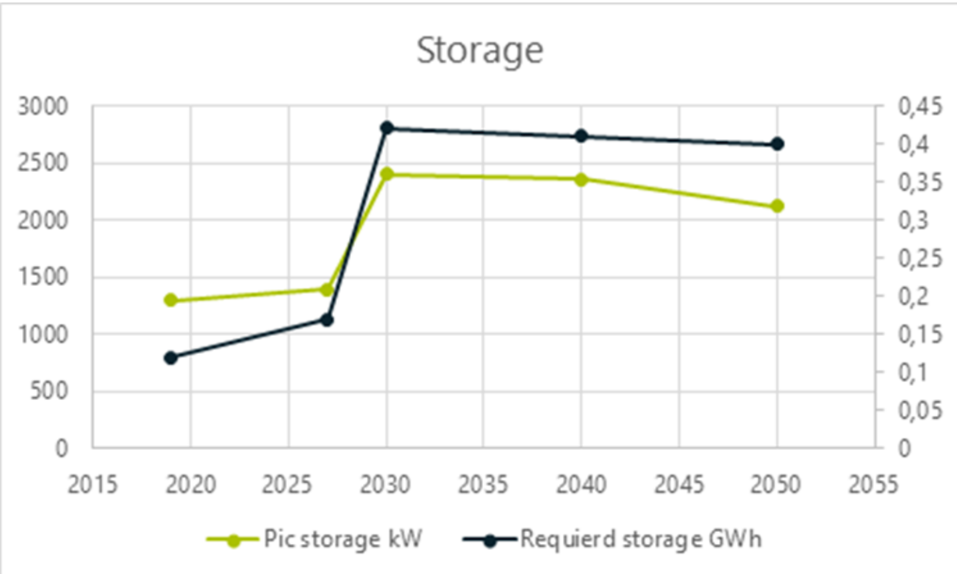


Figure 78, Peak and annual PV storage.

8.4.5 Robust smart energy hub concept(s)

8.4.5.1 Robust smart energy hub concept(s)

The simulation also examined the alignment between the demand for energy and the PV production at Larnaca International Airport using the actual existing PV plant characteristics and the terminal building thermal envelop and demonstrated that most of the time the PV energy could be usefully used. In practice though the actual PV production has been curtailed (restricted) by the national grid operator on the premise that the national grid cannot absorb the excess energy produced by the PV plant and the problem is that the curtailment applied is much greater to the extent that it cuts off energy that would have been beneficially used by the airport.

Consequently, Larnaka Airport as a first step is considering the implementation of a robust smart energy hub to self-regulate PV production so it matches the airport's demand for energy, and thereby not generating any excess energy, thus preventing the national grid from interfering and cutting the energy produced by the PV plant. As a second step the airport will consider the introduction of battery storage for excess energy produced by the PV plant. This approach will ensure that all solar energy generated is used locally within the airport, minimizing the need to export surplus energy to the grid and reducing the impact of grid regulation constraints. To achieve this, Larnaca Airport is planning to implement an advanced smart energy control system that dynamically manages the generation, storage, and consumption of solar power.

The smart energy control system is designed to optimize the PV park's output by intelligently balancing supply and demand, thereby preventing excess energy from being exported and aligning with the zero-export policy. The system will adjust energy flows and storage operations, ensuring that the airport's energy needs are met efficiently and sustainably.

In addition to supporting zero export, the control system enhances the resilience and flexibility of the airport's energy infrastructure. It facilitates the seamless integration of renewable energy sources with existing energy systems and incorporates energy storage solutions to buffer against fluctuations in supply and demand. This comprehensive approach not only contributes to reducing greenhouse gas emissions but also advances Larnaca Airport's sustainability goals by promoting self-sufficiency and reducing reliance on fossil fuels.

Overall, the robust smart energy hub at Larnaca Airport exemplifies a forward-thinking model for sustainable energy management in aviation, positioning the airport as a leader in adopting innovative and environmentally responsible practices.

8.4.6 Conclusion

Dynamic simulation modelling has been used to identify and quantify potential energy conservation measures at the Terminal Building at Larnaka International Airport, of the energy produced by the onsite photovoltaic (PV) plant for three milestone years, 2027, 2030 and 2040 and the simulation also examined the alignment between the demand for energy and the PV production. The analysis performed is relevant to the operation of Larnaka Airport and particularly to Hermes' Climate and Energy Road map.

Energy conservation and PV production are among the core measures included in Hermes Climate and Energy Road map to net zero, hence the decision to perform these simulations is consistent with the Energy Strategy of Hermes Airports and of Larnaka International Airport.

The thermal simulation modelling has identified that increasing natural ventilation during certain months and during specific hours of the day is an effective method to reduce electrical energy consumption by the HVAC systems without detrimentally affecting thermal comfort conditions for passengers and staff. Similarly, the simulation has shown that solar shading and increasing the set point temperature within the conditioned spaces of the airport also will yield significant energy savings. It was not within the scope of the thermal simulation modelling however, to consider the practical aspects of increasing natural ventilation and how to treat the fresh air before it is delivered into the Terminal, or the practical aspects of adding solar film and how the reduction of daylight would impact the perception and satisfaction of the customers.

The simulation demonstrated that a high level of self-consumption of Solar PV is possible when the plan is operating at full capacity and during periods when production exceeds the demand from the Terminal, the excess production could be used for charging electrically driven vehicles and ground service equipment operating at the airport. However, real life experience has shown that the national grid operator intervenes and applies curtailment i.e. cuts the PV production because the national grid cannot absorb the excess energy produced. The curtailment applied however im much greater than the excess energy produced by the PV plant and Larnaca Airport loses energy that would have been beneficially used. For this reason, as a first step to be implemented in the short term, it is planned to introduce a local smart energy system that will self-regulate PV production to match the energy demand of the airport and thereby prevent the national grid from externally accessing the PV plant and applying curtailment, while as a second step battery storage will be assessed for the excess energy produced.

With the help of the model Larnaca identified a huge potential to decrease the energy demand for cooling, without however examining the practical challenges of doing so or the impact on the passenger perception and experience. The latter was outside the scope of the simulation.

Regarding the energy production by the photovoltaic plant at Larnaka Airport the simulation has identified that during certain times of the year the energy produced can cover the needs of the

Terminal building for electricity. Also, there will be certain periods when PV energy production exceeds the energy requirements of the Terminal Building, and battery storage would be an option during those periods.

The excess energy produced by the PV plant and stored in the batteries could be used to charge electrically driven vehicles and ground service equipment operating at the airport.

Within the concept of the Smart Energy Hub, the information provided by the thermal modelling and PV production modelling could be used by Hermes to specify the performance requirements for and advanced energy management system and support decision making with regards to when to use each available source of energy from the mix available.

Annex 2: Contribution to the Knowledge Portfolio

According to the requirements set by the European Commission, an annex with the Contribution to the knowledge Portfolio should be included in the deliverable. Guidelines state that is standard access conditions apply, this section can be skipped. Since this document is not a formal deliverable and can be considered of public access, not confidential, does not contain any patent or any other rights subject to embargo, the Contribution to the knowledge portfolio is not applicable.

Table A1.1 – Contribution to the knowledge portfolio: Background

BACKGROUND – STATE OF THE ART AND DEVELOPMENT PLAN	
Owner(s)	TNO
Nature	Report
Registration/Protection	Not applicable
Description	Plan of approach for setting up TULIPS demo 1.3, including the state of the art on electric heavy duty trucks
Access conditions for research in the project / Limitations	Not applicable
Access conditions for Use / Limitations	Not applicable
Licensees in the project	Not applicable
Licensees for use	Not applicable

Table A2.2 – Contribution to the knowledge portfolio: Exploitable Foreground

EXPLOITABLE FOREGROUND	
Type of exploitable foreground	General advancement of knowledge
Exploitable Foreground (description)	Not applicable
Confidential	No
Foreseen embargo date	Not applicable
Exploitable product(s) or measure(s)	Not applicable
Sector(s) of application	Not applicable
Timetable for commercial use or any other use	Not applicable
Patents or other IPR exploitation (licenses)	Not applicable
Owner & Other Beneficiary(s) involved	Not applicable

Table A.2.3 – Contribution to the knowledge portfolio: Patents, Trademarks, Registered designs, etc.

PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC.	
Type of IP rights	Public access

Application reference(s) (e.g. EP123456)	Not applicable
Subject or title of application	Not applicable
Confidential	Not applicable
Foreseen embargo date	Not applicable
Applicant(s) as on the application	Not applicable
URL of application	Not applicable

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