Andrei Morch\textsuperscript{1}, Lorenzo Laveneziana\textsuperscript{2}, Ingvald Erga\textsuperscript{3}, Gabriele Restaldo\textsuperscript{4}, Mauro Odisio\textsuperscript{4}, and David Chiaramonti\textsuperscript{2}

\textsuperscript{1}Department of Energy Systems, SINTEF Energy Research Trondheim
\textsuperscript{2}Department of Energy, DENERG Politecnico di Torino Torino
\textsuperscript{3}Department for Airside Operations Avinor Sola
\textsuperscript{4}Maintenance Department SAGAT

June 24, 2024
Abstract—Reduction of transport emissions, including critical infrastructures like airports, is a consistent part of the European political goals. Introduction of local renewable energy sources into a complicated energy system as a modern airport requires dedicated optimisation tools and methods. The present paper presents results of comparing two modelling tools OSeMOSYS and Integrate applied for configuration of two case airports: Torino (Italy) and Stavanger (Norway) respectively. The results outline optimal paths for sustainable decarbonisation creating integrated energy systems, which rely on utilisation of locally available resources as PV, Wind and biomethane or deployment of a local hydrogen network, the latter a fundamental enabler for a long-term strategy based on hydrogen. The study highlights the importance of dedicated modelling tools for planning and operation phases for integrated energy systems.

Index Terms—Integration of renewables, Integrated energy systems, Electrification of transport, Hydrogen economy

I. INTRODUCTION

A. Motivation and background

To achieve climate neutrality, the European Green Deal (GD) sets out the need to reduce transport emissions by 90% by 2050 (from 1990-levels). These goals were reaffirmed in February 2024 when the European Commission issued recommendation for a 90% net greenhouse gas emissions reduction by 2040 compared to 1990 levels. This recommendation complies with the advice of the European Scientific Advisory Board on Climate Change (ESABCC) and the EU’s commitments under the Paris Agreement. The document [1] emphasises decarbonisation of several types of transport, including road, maritime and air by introduction of zero-emission vehicles, aircrafts and vessels.

These environmental goals inspired initiation of the EU GD project TULIPS, covering 17 real-life demonstration projects in four airports, which in total involve 11 Member States across Europe [2]. Several demonstrations focus on reducing vehicle emissions. Other test facilities for recharging aircraft with electricity and hydrogen, introduce and optimise large-scale supply of Sustainable Aviation Fuel (SAF). The present paper presents results from Smart Energy Hub activity.

A modern airport represents an extremely complicated energy system requiring very high operational reliability, being a part of critical infrastructure. Introduction of local renewable energy sources, gradual electrification of ground operations and aircrafts will radically change the picture. An optimal configuration of an integrated energy system, incorporating several energy carriers, becomes a non-trivial task, requiring dedicated optimisation tools and methods. The present paper presents results of comparing two modelling tools applied for configuration of two case airports: Torino (IT) and Stavanger (NO). Beside difference in the geographic location, the two airports share similar characteristics in their energy consumption and mix, offering the opportunity of a comparative case study.

B. Related literature

One can find several definitions of Integrated Energy Systems (IES) with minor variations, but the main property of IES or Multienergy Systems (MES) is moving from a single energy carrier towards a coordinated utilisation of multiple energy carriers [3]. The concept of IES received a strong political support after publication of Vision 2050 [4] in 2018, when the Pan-European integrated energy system was defined as an ultimate goal for supplying the society and paving the way for a fully carbon-neutral circular economy. The document drew a visionary concept of future “System of Systems” placing the electricity grid in the centre as its backbone.

The effort of the EU in realising its Sustainable, Smart and Safe Mobility Strategy is also reflected by the numerous projects dedicated to the decarbonisation of crucial transport
TABLE I

<table>
<thead>
<tr>
<th>Activity</th>
<th>Stavanger 2019</th>
<th>Stavanger 2022</th>
<th>Torino 2019</th>
<th>Torino 2022</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passengers [10^6]</td>
<td>4.31</td>
<td>3.58</td>
<td>3.95</td>
<td>4.19</td>
</tr>
<tr>
<td>Aircraft movements [10^3]</td>
<td>75.2</td>
<td>69.2</td>
<td>43.3</td>
<td>42.6</td>
</tr>
<tr>
<td>Gross floor area [10^3 m^2]</td>
<td>60.9</td>
<td>174</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy consumption [GWh]</td>
<td>18.1</td>
<td>16.8</td>
<td>24.6</td>
<td>21.9</td>
</tr>
<tr>
<td>Electricity</td>
<td>15.2</td>
<td>13.5</td>
<td>15.1</td>
<td>13.3</td>
</tr>
<tr>
<td>District heating</td>
<td>2.70</td>
<td>3.04</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Auxiliary power</td>
<td>0.20</td>
<td>0.22</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Natural gas</td>
<td>-</td>
<td>-</td>
<td>7.83</td>
<td>7.01</td>
</tr>
<tr>
<td>Diesel</td>
<td>-</td>
<td>-</td>
<td>1.41</td>
<td>1.53</td>
</tr>
<tr>
<td>Energy indicators</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consumption [kWh · m^2]</td>
<td>0.30</td>
<td>0.28</td>
<td>0.14</td>
<td>0.13</td>
</tr>
<tr>
<td>Consumption [kWh · pax^1]</td>
<td>4.20</td>
<td>4.69</td>
<td>6.24</td>
<td>5.22</td>
</tr>
</tbody>
</table>

infrastructures. Beside TULIPS, which supported this work, three other projects are contributing to shape the future of green airports: Stargate [5], OLGA [6] and ALIGHT [7]. Taken together, all these projects are exploring a comprehensive range of solutions and initiatives aimed at making airports more sustainable. In broader terms the concept of IES has been studied in H2020 project eNeuron [8], where a dedicated toolbox for planning and operation of integrated local energy community hubs has been developed.

One can conclude that transport hubs as airports and ports have become critically important targets for the decarbonisation process, which among other things requires optimal interaction or coupling between several energy carriers. The optimal management of multiple energy carriers is vital for an efficient operation of IES in terms of both energy, emissions, and economic sustainability. This highlights the importance of dedicated modelling tools for planning and operation phases.

C. Contributions and organisation

The present paper is organised as follows: the METHODOLOGY section presents the energy system optimisation approach and introduces the tools used for the analysis; moreover, the major sources of uncertainties in energy planning are discussed. Next, two sections are dedicated to the case studies of the two airports: the results of the simulations conducted by SINTEF for Stavanger airport and by Politecnico di Torino for Torino airport are illustrated. Finally, the CONCLUSION section presents the main takeaways drawn from the modelling experience at the two airport sites.

II. METHODOLOGY

A. Uncertainties and limitations

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.

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.

The recent energy crisis in Europe reminded how challenging it can be to predict prices for conventional energy carriers. Another important source of uncertainty concerns the supply of alternative energy carriers, such as biomethane and green hydrogen. While the REPowerEU plan [9] strengthened EU’s commitment to the development of value chains for these gases, the actual success of these policies is hard to predict. For hydrogen, in particular, major investments would be needed to build or adapt gas infrastructures to its transportation [10]. Therefore, the establishment of a successful hydrogen economy at the airport cannot be uncoupled from the development of the local energy system [11].

B. Modelling tools to support airports transition

Both the Torino and Stavanger case studies employed tools from the family of energy system optimisation models (ESOMs). ESOMs rely on an optimisation methodology to determine the configuration of the system which minimises an objective function, typically the total net present costs. Total net costs can consider several items, from investment and operational expenditures to levies and incentives. The optimisation of the system can be constrained by technical, economic and environment objectives (e.g., GHG emissions reduction). ESOMs are gaining popularity for the assessment of distributed energy systems [12]–[15], and a growing pool of modelling frameworks is being developed [16]. Distributed energy systems are fundamentally characterized by locating energy production systems closer to the point of use [17], [18]. Several comparative description of modelling tools for integrated energy systems were recently made and presented in comprehensive review papers as [19], [20] and [21]. This makes it unnecessary to repeat such overview in the present paper.

SINTEF Energi applies “Integrate” [22] (formerly eTransport), a software system for optimisation of integrated energy systems. The tool combines Linear Programming (LP) and Dynamic Programming (DP/SDP). 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.

The assessment of the Torino case-study was conducted by Politecnico di Torino with OSeMOSYS [23], a widespread, open-source framework to generate energy system models.
One key feature of the OSeMOSYS framework is the possibility the represent the evolution of key input parameters (e.g., demand, energy and technology prices) along the modelled horizon. This makes it particularly suitable to explore the optimal transition of the airport under future energy scenarios.

Both the employed models mainly rely on linear representation of the energy system, although integer decisions are implemented to improve the physical representation of selected components (e.g., heat-power ratio and minimum operation levels of CHP units).

III. The Norwegian case: Stavanger airport

The Stavanger airport Sola is one of the principal airports in Norway with 3.6 million passengers in 2022 (see Table I). In addition to international and domestic flights, it is the main helicopter hub for the South-western part of Norway, servicing the Norwegian offshore petroleum sector. Sola airport is a part of Avinor concern, wholly-owned state company operating 43 airports in Norway with app. 50 million passengers annually. The Avinor’s group strategy for the period 2022-2025 is to become an active supporter of sustainable aviation enabling the Norwegian aviation to reach its goal to be fossil-free by 2050. Apart from TULIPS, Stavanger airport has participated in a six-year national innovation and demonstration project Elnett21 [24], where large stakeholders such as ports, industrial parks and airports are working together to prepare themselves for the challenges that electrification will entail. Outcomes of Elnett21 have been used as basis for creation of the target scenarios in this study.

Configuration of Sola was initially based on combination of two main energy carriers: electricity and heat without any coupling between these two in regular operation. It includes the following components:

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

The Avinor’s corporate goals include among other things a gradual test implementation of electric regional commuter aircrafts for nine passengers during the next years. The aircrafts will be tested on a short route between Stavanger and Bergen with app. 30 min flight time. With expected energy consumption app. 200 kWh pr trip/plane (the figure was provided by the vendor in 2023 and appears to be close to numbers stipulated in [25]), two planes are estimated to have a demand of 12 MWh pr. week. 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. This increase presumes careful avoiding of coincident charging of several planes and refers to one-minute sampling.

In addition, the airport’s overall demand continues to grow due to electrification and, according to outcomes of Elnett21 project, is expected to reach the base load of 5 MW, while the total possible max load may reach 15 MW by 2030. Several solutions are applicable, including upgrading capacity of the existing substation 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 [26]. 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 study modelled three separate periods: 2022-2025/2025-2027 and 2027-2030, where the model considers several investment options (in italic) for compensating this:

- Photovoltaic: PV1; PV3; PV4 - three separate installations with 2 MW max generation capacity each.
- Wind power: Wind - 4x250 kW windmills as single installation. The model uses Vestas V29 225 as a reference turbine, relating to 2019 production data as generation profiles. With the allowed max height of 30 meters, it demonstrates mean capacity factor of 25.7% for Stavanger area.
- Combined Heat and Power: CHP - 500 kW gas engine, with heat as operational model priority. The prices are approximated from the airport’s previous study, operational costs estimated as 5% of the investment costs. The price for biomethane refers to the current levels in Stavanger area.
- Additional battery covering daily deficits for charging airplanes: BESS - 300 kWh
- Extension of the grid: GRID2 - capacity increase with 10 MW, represented by so-called construction fee – one time contribution to the local DSO, according to the Norwegian regulatory practice.

![Energy carriers in Stavanger airport.](image)

The foreseen interaction between different energy carriers at Stavanger airport is presented in Figure 1. The new layout of the energy system is presented in Figure 2, where the investment options are shown with stippled lines.

Unless special restrictions are set, the Integrate tool runs optimisation in combining different investment options in the stipulated timeline. The results represent ranking of these combinations (in our case ten) and definition of the optimal
Fig. 2. Simplified connection diagram for Stavanger airport (stippled lines indicate investment options)

Fig. 3. Optimisation results for Stavanger airport. Upper part: ranking of combination of investment options. Lower part: operation profile for CHP (one week).

IV. THE ITALIAN CASE: TORINO AIRPORT

Torino airport has long been committed to reducing its environmental footprint by deploying more energy efficient solutions in airport operations. The overarching ambition of the airport is to attain net-zero emissions from its Scope 1 and 2 activities in 2050. On this track, Torino airport is targeting a 55% emissions reduction (with respect to 2010 levels) in 2030, alongside the reduction of its primary energy consumption and the sustained increase of renewable energy usage at the airport site. In parallel, the airport is on the way to increase air traffic, targeting to nearly double the number of passengers by 2030. This is expected to lead to additional electricity demand.

In this work, cost-effective development pathways to comply with 2050 targets were studied for Torino airport using OSeMOSYS. The potential investment alternatives are shown in Figure 4. At the core of the energy system lies a microgrid concept, constituted by a PV plant, storage technologies (battery and hydrogen) and a trigeneration unit based on a solid oxide fuel cell (SOFC). The major novelty of this solution is in the innovative SOFC technology [28] which can run on different blends of natural gas/biomethane and hydrogen. Hydrogen can either be produced on-site through electrolysis or potentially imported from external sources. Biomethane is virtually imported in the airport energy system through Guarantees of Origin (GO). The PV system can be either installed on roofs or ground. The annual production of renewable electricity was estimated using SANDIA model [29] to 1.18 GWh/MW for flat rooftop PV and 1.36 GWh/MW for 30°-tilted ground-mounted PV. Excess renewable generation can be stored through Li-ion batteries (0.25C). The generation of renewable electricity can be coupled with heat pumps to decarbonise space heating. Air-to-Water (A2W) heat pumps with a COP of 2.5 were considered.

In this work, we simulated the optimal development pathway of the airport under three different circumstances: a hydrogen-based scenario (H2); a hydrogen based-scenario with external hydrogen supply (H2 - IMP); a pure electrification scenario (ELCTR). The H2 and H2 - IMP scenarios depict transition pathways relying on the prospected development of hydrogen technologies, whereas the ELCTR strategy is based on technologies at a high readiness level. Under hydrogen-based scenarios, capital and maintenance costs of hydrogen technologies drop as much as 80% already in 2030 [30], [31]. In the H2 - IMP scenario, the possibility to purchase hydrogen from an external supply after 2040 is envisaged, aiming at depicting the inclusion of the airport in a local hydrogen valley. A quite affordable price of 2.0 €/kg was assumed. Current production prices for green hydrogen falls
in a higher range (around 3 to 7 €/kg [32]). Still, costs related to hydrogen production are projected to dramatically drop by 2040, reaching even below 1 €/kg [33], [34]. In addition, relying on a nearby hydrogen valley for the supply is expected to reduce delivery costs [35], so that the assumption of 2.0 €/kg can be substantiated in the long term. In the scenario with pure electrification, decarbonisation objectives can solely be achieved through PV, batteries and electrification measures. Biomethane can be purchased only until 2045. All the scenarios assume the decarbonisation of the electricity grid [36].

The increase of electricity demand and the diversification of its provision are common traits to all scenarios (Figure 5). This is partly due to the rise of airport activities but this contribution is limited, as the analysis was confined to Scope 1 and 2 domains, mildly affected by increased air traffic. The major driver is thus electrification of space heating. This is evident in the ELCTR scenario, where the imposed phase-out of natural gas and biomethane leads to full electrification of heating between 2030 and 2050. As a result, the electricity demand in 2050 rises by more than 30% with respect to 2030. In hydrogen-based scenarios, the rise of electricity demand is limited to 15%, as decarbonisation of heating is achieved through electrification but also fuel switching to biomethane and cogeneration. The provision of electricity is more diversified too, with SOFC giving a relevant contribution to the airport’s on-site production.

With SOFC fuelled with natural gas the costs of the medium-term transition can be reduced. Nevertheless, as decarbonisation objectives get more tight, there is the need to provide a green blend, opting for more expensive fuels. The greening of the blend in the ’30-’40 period is primarily achieved through the purchase of biomethane as a transitional fuel. The on-site production of hydrogen amounts to a minor share of the fuel cell demand (about 25% in 2050), due to the limited space available for PV installation and the overall low power-to-power efficiency. Consequently, sustained purchase of biomethane or externally produced hydrogen is needed.

As decarbonisation objectives grow tight, the economic benefits of the fuel cell system are reduced. Consequently, part of the SOFC capacity installed before 2030 is decommissioned in the last decade. The importance of the availability of an affordable hydrogen supply emerges in the H2 - IMP scenario, where a larger-size fuel cell can be maintained with a green blend. Under this scenario, the airport could satisfy 65% of its electricity needs by on-site production, although the dependency on external gas supply would increase.

In the ELCTR scenario, up to 10 MWp PV system is installed and a 5.0 MWh battery pack is needed to absorb excess renewable generation. When relying on electricity-based measures, cost-effective and decarbonisation strategies tend to coincide and the development pathway see a gradual increase of PV, battery and heat pump capacity towards 2050. The self-production of electricity decreases with respect to hydrogen scenarios (slightly less than 50% in 2050) but the reliance on gas imports is minimised.

V. CONCLUSIONS

Stavanger and Torino airports, being similar in their size and operational characteristics, demonstrate different approaches in selection of the transition paths. Stavanger focuses on solving very specific short-term challenges, i.e. rapid increase of the load, and selects more mature decarbonising technologies as PV, windpower and biomethane. Torino airport emphasises long-term objectives, comparing transition pathways based on the prospected development of hydrogen with more mature technologies.

Despite these principal differences, both airports recognise the necessity to increase self-sufficiency and introduce energy coupling for more flexible 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. Independently on the latitude, PV remains a key part of the strategy of the two airports towards self-sufficiency. Cogeneration systems can further decrease reliance on electricity grid, but local supplies of green fuels must be secured. Availability of biomethane enables quick, environmentally friendly deployment of CHP and can bridge between current consumption of fossil gas and electrification. Integration of the airport in a local hydrogen network appears as a fundamental enabler for fuel cell-based strategies, as on-site hydrogen production is limited by space availability. 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.

ACKNOWLEDGMENT

The project “TULIPS” has received funding from the European Union’s Horizon 2020 Research and Innovation Programme under Grant Agreement No.101036996
REFERENCES


