CO-OPTIMIZATION OF RESILIENT AIRPORT ENERGY HUBS FOR FLIGHT ELECTRIFICATION AND HYDROGEN PROPULSION

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ABSTRACT

Flight electrification and hydrogen propulsion represent major technologies for decarbonizing the aviation industry. Powering these types of aircraft requires associated ground infrastructure developments at airports. A hybrid airport energy hub is developed comprising a series of electrochemical and storage components, whilst connected to the power and hydrogen grids. A co-optimization framework is deployed for the simultaneous design and operational scheduling against ground and airborne demands at minimum annual cost of energy and capital. Uncertainty associated to economic factors and the operation of the system is quantified through Monte Carlo simulation. Variance-based Sobol sensitivity analysis is conducted to identify the major contributing components to overall uncertainty. Resilience is introduced as an additional optimization objective, yielding system design and operational strategies able to react to disruptions in grid electricity supply. An annual cost penalty of 42.8% is accrued for increasing resilience from 0 to 55% when connected to a power grid with today's supply capacity. The cost penalty of increasing resilience drops to 4.7% in the case of a future power grid with increased capacity. This work sheds light on the potential and limitations of resilient airport energy hubs and draws directions for the development of a decarbonized aviation sector.

1 INTRODUCTION

Mitigating the environmental impact of air transport constitutes a primary objective for passengers, manufacturers, and airliners. Flight electrification and hydrogen propulsion are rendered as the main drivers towards achieving the ambitious national and European environmental goals (Littorin, 2021; Clean Hydrogen Joint Partnership, 2021). Despite the anticipated environmental benefits (Cappuzzo et al., 2020; Petrescu et al., 2020; Sahoo et al., 2020; Salem et al., 2023), questions arise with regards to ground infrastructure to power such aircraft (Vouros et al., 2021). Sustainable airport ecosystems present the potential to not only enable electrified and hydrogen-powered aviation, but also interact and support urban and regional energy grids (Zhou, 2022). The next five to ten years have been identified as a critical period for airports to adapt to electrified and hydrogen-powered aviation (Gu et al., 2023).

Airport electrification has been majorly studied from the aspect of powering ground facilities. An optimized solar-battery system was presented by Baek et al. (2016) to address the planned expansion in terminal power needs for Incheon International Airport. A multi-input multi-output model was developed for assessing the impact of electrification of airport ground support systems on CO_2 emissions (Kirca et al., 2020). Savings of up to 60% were calculated relative to conventional ground support operations. The integration of electricity and heating and cooling systems at Changsha airport was analyzed by Jin and Li (2023). The impact of electricity price on the share of grid-supplied power was shown to be critical during the intraday optimization.

The possibility of aircraft taxiing with external electric towing was investigated as a means for reducing carbon emissions in the vicinity of airports (Salihu et al., 2021), yielding carbon dioxide (CO_2) emissions reductions of up to 95% at a cost of 20% higher taxi times, compared with traditional taxi solutions. A hydrogen-solar-storage system was designed by Xiang et al. (2021) for electrifying airport ground systems and aircraft auxiliary power units. It was found that a concurrent reduction can be achieved in annual cost and carbon emissions by 41.6% and 67.29%, respectively. An energy demand analysis was carried out by Meindl et al. (2023) for identifying requirements for airport electrification to support regional hybrid electric aircraft at different timeframes. In the 2030 timeframe, it was found that 5608 tons of kerosene and 610 tons of sustainable aviation fuel (SAF) will be required, along with

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7233 MWh of electricity. In the 2040 timeframe, electricity requirements were estimated to be 75% higher than 2030, along with an additional 1291 tons of liquid hydrogen to eliminate kerosine and SAF.

The use of hydrogen for powering ground vehicles and aircraft was examined at Edmonton International Airport where hydrogen aircraft are expected to be in use after 2025 (Yusaf et al., 2024). Increased use of liquid hydrogen in aviation is expected to reduce landing and take-off (LTO) emissions (Testa et al., 2014), however extensive storage capabilities will become necessary (Janic, 2010). Development of hydrogen production, storage, and conversion infrastructure in airports presents economic and practical challenges (Degirmenci et al., 2023a), as well as safety implications (Degirmenci et al., 2023b). The aspect of resilience for electrified airport terminals and ground traffic was explored by Zhao et al. (2022). It was shown that increasing hydrogen permeability of the airport from 20% to 40% can increase the derived resilience index by 18%.

The economic competitiveness of green liquid hydrogen supply for airports to support hydrogen aviation was investigated by Hoelzen et al. (2023). It was concluded that hydrogen imports are of special importance for airports with weaker renewable energy resources. Still, transport of compressed or liquid hydrogen to airports through trucks was found to be costly, whilst the utilization of a pipe network would yield an economically more viable solution (Taha et al., 2023). Direct operating cost for hydrogen aviation can increase up to 70%, due to liquid hydrogen transport alone (Hoelzen et al., 2022).

Existing studies on airport electrification and hydrogen penetration focus primarily on powering ground facilities. A few works attempt a connection between ground and airborne demand. The aspect of resilience to unplanned disruptions is sparsely investigated. The scope of the present work is to establish a co-optimization strategy for the concurrent design and operational scheduling of airport energy hubs, powering both ground facilities and hybrid electric and hydrogen powered aircraft. The impact of uncertainty on economic evaluations and operation is quantified. Resilience becomes a major objective for the co-optimization, deriving airport design and operational scenarios that can handle unexpected disruptions, in connection with the regional power grid.

2 METHODOLOGY

2.1 System architecture

A hybrid energy system is developed comprising components for energy conversion in the vicinity of an airport, as illustrated in **Fig. 1**. The system resembles a future layout for regional airports. Sweden does not have an established natural gas pipe network, hence it is considered that hydrogen is externally supplied in gaseous and liquid form through tube trailers and tank trailers. A corresponding system of storage tanks for compressed gas and liquid hydrogen is installed. A compressor is adjacent to the compressed gas hydrogen (CGH2) tank whilst a liquefaction plant is considered in connection to the liquid hydrogen (LH2) storage tank. CGH2 is primarily used for occasional generation of electricity locally, conversion to LH2, but also powering smaller aircraft. LH2 is exclusively used for propulsion.

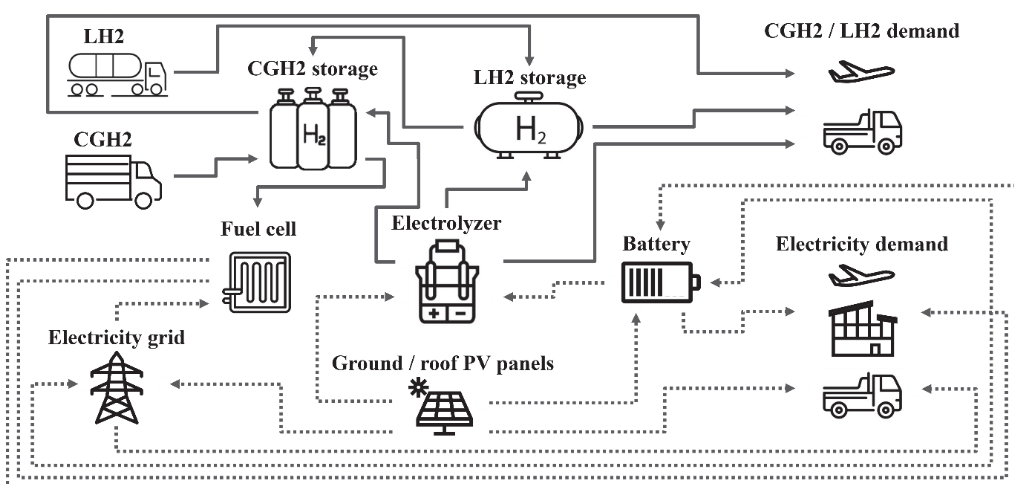

Figure 1: System architecture for airport energy hub

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Table 1: Specifications of system components

Component	Specifications
Battery	Type: Lithium-ion, Normal charge: 20% to 80%, Max charge/discharge rate: 10%, Capital cost: 100 EUR/kWh, Depreciation: 10 years
Electrolyzer	Type: Proton exchange membrane (PEM), Efficiency: 67%, Capital cost: 600 EUR/kW, Depreciation: 20 years
Fuel cell	Type: Proton exchange membrane (PEM), Efficiency: 67%, Capital cost: 500 EUR/kW, Depreciation: 5 years
CGH2 tank	Max charge/discharge rate: 100 kg/h, Capital cost: 500 EUR/kg, Depreciation: 20 years, Compression and cooling energy: 12% of H2 LHV
LH2 tank	Max charge/discharge rate: 600 kg/h, Boil-off rate: 3%/h, Capital cost: 1250 EUR/kg, Depreciation: 20 years
PV panels	Area: 3,000 m^2 (roof) + 10,000 m^2 (ground), Performance ratio: 75%, Efficiency: 27%, Capital cost: 110 EUR/m^2, Depreciation: 20 years
Compressor	Type: reciprocating, Capital cost: 2000 EUR/kg/h, Depreciation: 20 years
Liquefaction plant	Capital cost: 2,000 EUR/kg/h, Depreciation: 20 years
Tube trailer (CGH2)	Min capacity: 100 kg, Max capacity: 300 kg, Transport price: 1.9 EUR/kg
Tank trailer (LH2)	Min capacity: 300 kg, Max capacity: 1350 kg, Transport price: 2.8 EUR/kg

The system is connected to the regional power grid, allowing bilateral exchange of electricity. Grid-supplied electricity is either used to directly charge electrified aircraft or ground vehicles, the airport terminal, as well as conversion into hydrogen. Electrochemical components, namely fuel cell, electrolyzer, and battery are essential for converting hydrogen into electricity, electricity into hydrogen, and storing electrical energy. Own production of electricity is implemented through roof- and ground-installed photovoltaic (PV) panels. Specifications for each component are provided in **Table 1**, according to Elberry et al., 2021, Krasae-In et al., 2010, Reddi et al., 2018, and Xiang et al., 2021.

A series of complex interconnections is possible between the different components of the system. For example, the battery system can store electricity provided by the grid, or the PV panels, or the fuel cell. But it can also sell electricity to the grid, or power the electrolyzer or the ground or airborne demand directly. Dotted gray lines represent the possible flow streams for electricity across the system, whilst continuous gray lines illustrate possible hydrogen streams. The proposed architecture allows for an energy hub to operate in connection to the power grid whilst exploiting relative flexibility in demand response and concurrent power supply to the grid when boundary conditions allow. The major parameters that form the boundary conditions to the system operation are the following:

- Demand in electricity and hydrogen by the airborne and ground consumers
- Market factors, particularly electricity and hydrogen prices
- Volatility in own generation of electricity through PV panels

2.2 Boundary conditions

Stockholm-Västerås regional airport is employed as a representative hub for regional flight electrification in this study. The city of Västerås constitutes an established and rapidly growing hub for industrial electrification in Sweden, therefore, investigations on a potentially electrified airport connected to the power grid is of high relevance and importance. An intermediate timeframe, namely 2035 is considered for the assessments. A combination of historical data, public information, literature, and engineering judgement is utilized for assembling demand profiles for electricity and compressed gas and liquid hydrogen. The examined duration ranges one full week, which is deemed as a representative periodicity for airport operations. A time step of 1 hour is selected to comply with the resolution adopted by the electricity market in Sweden.

Currently, the airport serves approximately 100,000 passengers per year through commercial, business, and training flights. The fleet mix comprises 150-pax single-aisle turbofans 50-pax regional turboprops, 20-pax business jets, and 4-pax trainer aircraft. Public information on flight schedules is only available for the commercial passenger flights therefore reasonable assumptions were made for the remaining private flights. The accrued flight schedule is presented in **Fig. 2.a**. A variety of electrified and hydrogen-powered propulsion configurations is considered, following suggestions in the open literature and own research within the authoring research group (Bermperis et al., 2024a; Bermperis et al., 2024b; Vouros et al., 2021; Kavvalos et al., 2021). The exact number of existing aircraft to be

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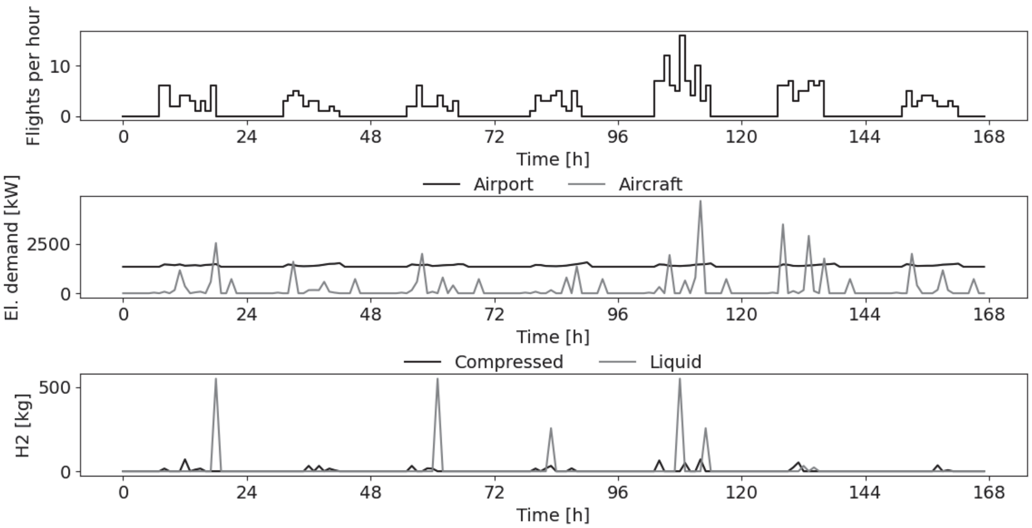

Figure 2: (a) flight schedule profile; (b) electricity demand for airport and aircraft; (c) compressed and liquid hydrogen demand.

converted by 2035 is unknown, so a balanced share was assumed in the context of this study, as summarized in **Table 2**. A low-intermediate degree of hybridization, namely 20%, is adopted for the hybridized propulsion variants (Bermperis et al., 2024a). Information about the terminal electricity demand at Västerås Airport is not openly available therefore an extrapolation is done based on corresponding consumption at Stockholm Arlanda airport, based on terminal relative size, number of stores, parking space, and runway area (Deng et al., 2018). The resulting profiles for electricity and hydrogen demand at ground and aircraft level are presented in **Fig. 2.b** and **Fig. 2.c**.

Historical data is used for electricity price, specifically prices for Sweden's energy region SE3 during the first week of December 2023. The selected period demonstrates a representative variation in electricity prices during winter months. Prices for compressed gas and liquid hydrogen are estimated on the basis of being produced by green electricity. Profiles from hydrogen market values are upscaled to match green-electricity-derived orders of magnitude. Solar radiation data for the same period are derived from public weather stations. It is noted that solar radiation during December in Sweden is relatively low which renders a challenging operational scenario for the airport energy hub.

2.3 Co-optimization strategy

A linear mathematical representation is adopted for the system components and their interconnections. Linear modelling allows for the comprehensive assessment of large-scale systems under reasonable computational overheads. A total of 30 continuous operational variables occurs out of all possible connections within the system, whilst 8 binary variables are added for the on/off operation of the system components. Additionally, 7 design variables are needed for describing the size of energy conversion and storage components. A total of 26 operational constraints are introduced to account for maximum and minimum capacities and charge or discharge rates for the system components.

Optimizing the size of the system components shall be done under optimal operating conditions, whilst operational optimization shall be done for an appropriately sized system. A dual-level optimization strategy is developed for concurrent sizing and operational scheduling, as illustrated in **Fig. 3**. Specifically, a mixed integer linear programming (MILP) optimizer is employed for deriving optimized operational schedules for the system. MILP has demonstrated efficiency and robustness in

Table 2: Aircraft sizes, propulsion architectures, and fleet mix

Aircraft size	**Number of aircraft per propulsion architecture**				
	Conventional	**Hybrid electric**	**Hydrogen electric**	**Fully electric**	**Hydrogen**
4-pax	108	0	30	22	6
20-pax	36	20	20	36	3
50-pax	5	0	2	1	3
150-pax	2	0	0	0	0

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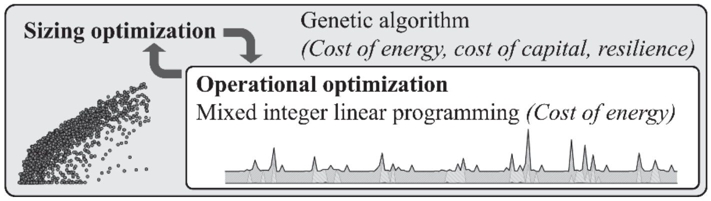

Figure 3: Overview of co-optimization strategy

optimizing complex energy systems within long- and short-time horizons (Saletti et al., 2022). The objective for the MILP is to minimize the cost of energy associated with the operation of a given system within the selected weekly time frame. This cost involves external supply of electricity and hydrogen in compressed gas or liquid form, on-site hydrogen production, compression, and liquefaction, as well as negative costs from possible sale of electricity to the grid.

Optimal sizing for the system components is achieved through a genetic algorithm (GA) which is wrapped around the MILP scheduler. The objective for the GA is to minimize the annual cost for the system. Annual cost comprises both the weekly cost of energy accrued from the MILP and scaled to 52 weeks, as well as the annual cost of capital for the system components. Multiple local minima are observed in the response of this objective function therefore the GA is preferred over a gradient-based optimizer. It is noted that optimal sizes for the components could also be derived as part of the MILP solution. However, it is decided to decouple the optimization in two stages to allow for multiple objectives to be added into the sizing routine. This will enable tradeoff studies between cost and resilience, as will be shown in section 3.4.

3 RESULTS

3.1 Optimal sizing and operation

The co-optimization strategy for sizing and operation is deployed for the case of Västerås Airport, as described in sections 2.1 – 2.4. Industrial electrification grows rapidly in Sweden, therefore a steep rise in electricity demand is anticipated in the years to come. Nowadays, the surplus grid capacity in Västerås area is in the order of 1MW. An estimate for 2035 is made in the context of this study and a surplus grid capacity of 4MW is considered. This is deemed as a reasonable development for the grid based on expected increase in renewable penetration and transmission capacity expansion in Sweden's SE3 energy region. The accrued optimal sizing for the system components is summarized in **Table 3**. Relatively small sizes are obtained for the fuel cell and the liquefaction plant, demonstrating the relatively limited capabilities for on-site electricity generation through hydrogen as well as on-site production of LH2. It is therefore expected that the system will rely on external supplies, as well as its own storage of electricity and hydrogen.

The resulting optimal electricity streams are presented in **Fig. 4.a**. Baseline electricity demand, which primarily powers ground facilities and vehicles, is covered by external grid electricity supplies in combination with stored electricity from the battery. A minor contribution is added by the PV panels. The charging operation for the battery with electricity price superimposed is illustrated in **Fig. 4.b**. It is observed that the battery is charged mainly by the power grid, and this happens when electricity price is low. Small contributions from the PV panels are occasionally added to the charging process. Battery discharge is shown in **Fig. 4.c**. The battery releases electricity either to the airport or even back to the regional grid when electricity price is high. This is the added value of MILP in operational optimization: the algorithm prevents the airport from costly purchase of electricity whilst at the same time creating revenue streams which improve the economic sustainability of the system. Optimized CGH2 and LH2 streams are illustrated in **Fig. 5.a** and **Fig. 5.b**. The demand for CGH2 is met by a combination of tank-stored hydrogen and direct compression after electrolysis. The electrolyzer is utilized in the production of CGH2 either when grid electricity price is low or when surplus is stored in the battery.

Table 3: Optimal sizing derived from co-optimization for annual cost of energy and capital

Battery [MWh]	Electrolyzer [MW]	Fuel cell [MW]	CGH2 tank [kg]	LH2 tank [kg]	Compressor [kg/h]	Liquefaction plant [kg/h]
40	1.8	0.6	240	600	26	4

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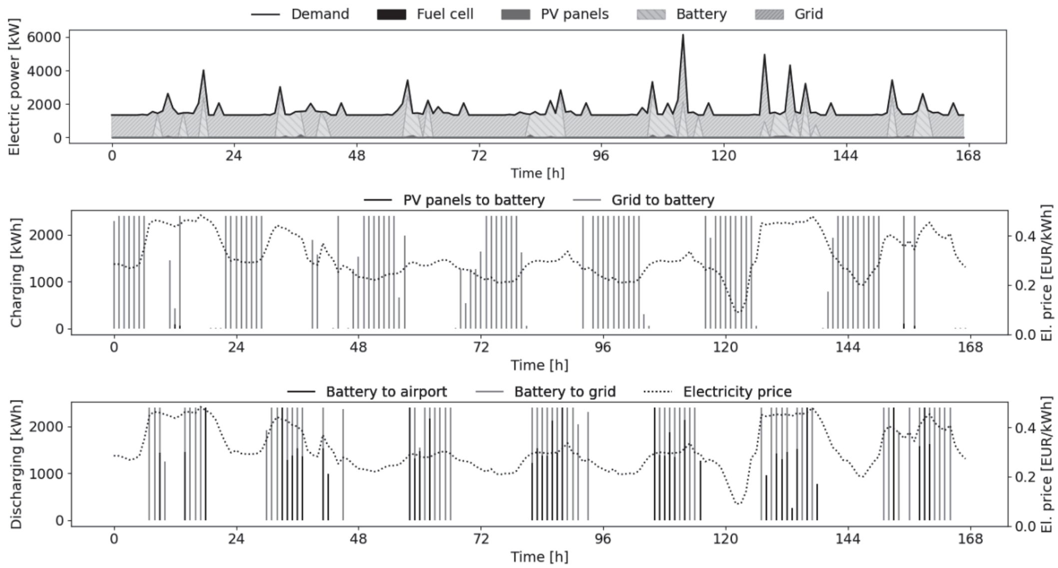

Figure 4: Optimal electricity streams: (a) electric power; (b) battery charging; (c) battery discharging

Charging of CGH2 tank through the electrolyzer is done when the cost of on-site production is lower than supplier's price, as shown in **Fig. 5.c**. Supply of LH2 to the airborne demand is done by the tank storage system, filled by external supplies, as in **Fig. 5.d**. On-site liquefaction is an energy intensive process which would require increased capacity in externally supplied electricity. This depicts the need for upscaling grid capacity for primary generation and transmission of electricity if on-site LH2 production is intended in future energy hubs.

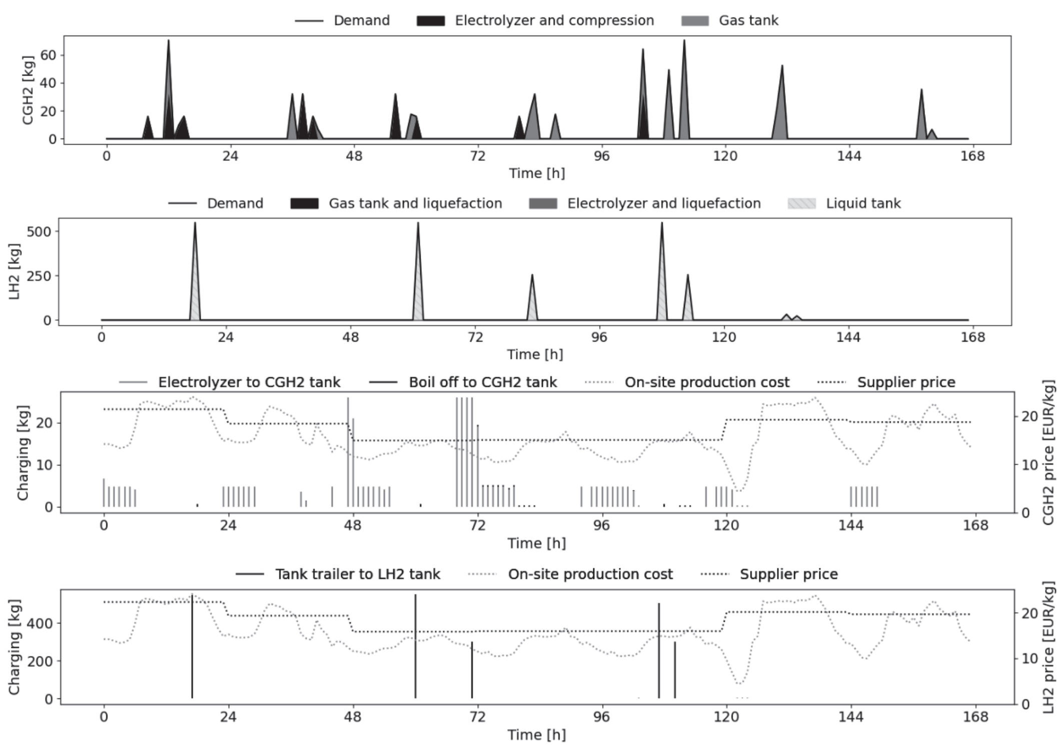

Figure 5: Optimal hydrogen streams: (a) compressed hydrogen; (b) liquid hydrogen; (c) charging of compressed hydrogen tank; (d) charging of liquid hydrogen tank.

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Table 4: Breakdown of annual cost of energy and annual cost of capital

Annual cost of energy = 6.1 MEUR			
Electricity streams	**CGH2 streams**	**LH2 streams**	**Conversion**
58.6 %	0.5 %	32.9%	8%

Annual cost of capital = 0.8 MEUR							
Battery	**Electrolyzer**	**Fuel cell**	**CGH2 tank**	**LH2 tank**	**Compressor**	**Liq. plant**	**PV panels**
60.4 %	9.6 %	8.8 %	1.1 %	6.6 %	0.5 %	0.1 %	12.9 %

3.2 Cost analysis

The annual cost evaluated in this work comprises the annual cost of energy for operating the facility and annual cost of capital for purchasing the equipment. Annual cost of capital is calculated as a function of the purchase price, interest rate, and depreciation time for each component. An interest rate of 4% was considered which represents today's market figures in Sweden. Individual purchase prices and depreciation times are used for each component, based on literature suggestions, as listed in **Table 1**. Annual cost of energy and annual cost of capital, along with a breakdown into major components are provided in **Table 4**. It is observed that 58.6% of the energy cost is attributed to direct electricity flows depicting the impact of electricity price on system economics. Direct LH2 flows take 32.9% of the energy cost, demonstrating the need for economically sustainable LH2 production on-site. Conversion of energy is kept at relatively low rates due to limitations in electricity grid surplus capacity, yielding an 8% of energy costs for conversion. Even lower shares are calculated for direct CGH2 flows under the present boundary conditions for system operation.

Battery dominates the annual cost of capital, with a share reaching up to approximately 60%. The role of electricity storage is critical for hybrid energy systems due to high round-trip efficiency relative to counterpart technologies based on hydrogen. It is therefore of the utmost importance for battery technology to continue growing and reducing capital costs. Corresponding costs for the electrolyzer, PV panels, and fuel cell approximately range between 9% and 13%, whilst lower shares are accrued for hydrogen storage tanks, compression system, and liquefaction plant.

3.3 Uncertainty quantification

Annual cost constitutes the objective in scheduling and sizing optimization for the system. Cost is a function of several volatile factors; therefore, uncertainty is inherently associated with economic evaluations. The importance of uncertainty in operational optimization was highlighted by Marzi et al. (2023). For a potential investment planned at a given timeframe, cost of energy and cost of capital are governed by the following market factors: electricity price, CGH2 price, LH2 price, and interest rate. Historical data ranging from 2013 to 2023 was collected. Appropriate standard deviations were calculated and assigned around the deterministic time distributions for electricity price, CGH2 price and LH2 price, as well as the value of interest rate employed in the analysis of sections 3.1 and 3.2. Gaussian statistical distributions were considered, truncated at three standard deviations from the mean value. The resulting coefficient of variation (COV) for each of the four uncertain parameters are (on average) 22% for electricity price, CGH2 price and LH2 price, and 32% for interest rate. A Monte Carlo simulation (Mooney, 1997) is conducted based on 1,000 points that comprise combined variations of the four uncertain parameters according to the adopted distributions. It is noted that the first four statistical moments of annual cost are checked for convergence, therefore the selected number of points is sufficient for reliable quantification of uncertainty. The resulting COV for annual cost is 17.4% which reflects the impact of input uncertainty on the economic evaluation of future development projects.

The distribution of cost of energy as function of time, both calculated in a deterministic and probabilistic mode, including 95% confidence intervals is presented in **Fig. 6.a**. Uncertainty levels are higher during times of high demand for electricity or LH2. A similar response is observed in the distribution of grid-supplied power, as shown in **Fig. 6.b**. The deterministic and probabilistic response of battery state of charge (SOC) is illustrated in **Fig. 6.c**. Nearly identical profiles are observed, associated with low levels of uncertainty. This is attributed to the indispensable role of the battery in the operation of the system, which renders the operation of this component reluctant to volatility in economic factors. On the contrary, higher uncertainty levels are obtained for the SOC of CGH2 tank, as in **Fig. 6.d**. The component is significantly affected by variations in electricity and CGH2 price,

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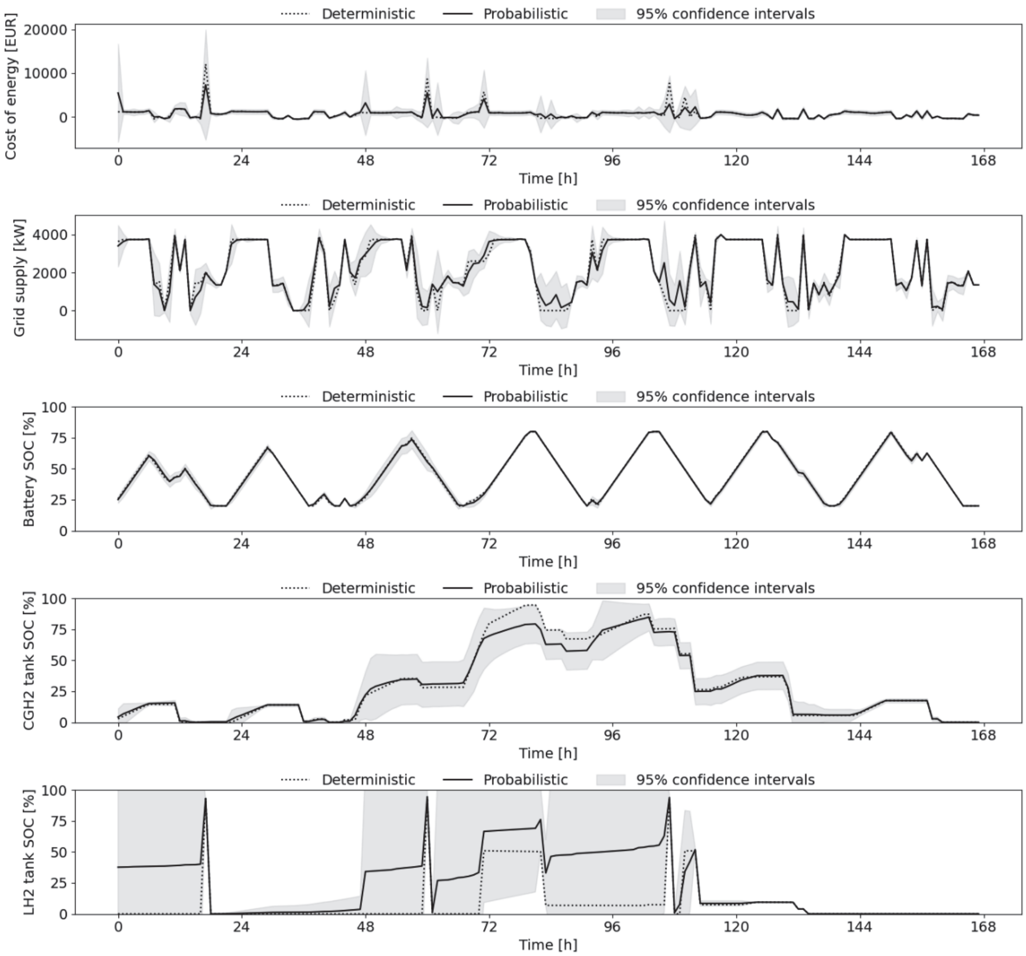

Figure 6: Uncertainty quantification: (a) cost of energy; (b) grid electricity supply; (c) battery state of charge; (d) compressed gas hydrogen tank state of charge; (e) liquid hydrogen tank state of charge

yielding discrepancies even between the deterministic and probabilistic simulations. The highest uncertainty is observed for the SOC of LH2 tank, **Fig. 6.e**. Discharging of the LH2 tank is consistent with LH2 powered flights, however the time of charging varies highly between the Monte Carlo simulated scenarios, as function of the relative difference between electricity price and LH2 price.

A variance-based sensitivity analysis is carried out to identify the contribution of each uncertain parameter to the overall uncertainty in annual cost. Hence, Sobol sensitivity indices (Nossent et al., 2011) are calculated, showing that electricity price dominates with an 82.1% contribution to overall uncertainty in annual cost. LH2 price follows with a substantial contribution of 14.5%, whilst CGH2 and interest rate are attributed with 2.5% and 0.9% contribution, respectively. Sobol sensitivity indices highlight the importance of stability in electricity market on the economic projecting for an energy hub.

3.4 Design for resilience

Volatility in supply combined with economic uncertainties, both due to increased penetration of renewables and geo-political circumstances, dictate the need for enhanced resilience in the energy systems of the future. Resilience is defined as the ability of the system to react to unexpected disruptions (Jasiūnas et al., 2021). As shown in sections 3.1-3.3, electricity price and consequently, electricity supply from the grid govern the operation of the entire system. It is therefore decided that resilience will be assessed relative to disruptions in the electricity supply from the regional grid.

Deterministic quantitative descriptors have been proposed to assess resilience (Martišauskas et al., 2022). In this work, a probabilistic approach is used for introducing disruptions in the grid electricity supply. Disruptions are profiled by two factors: frequency and magnitude. Therefore, different

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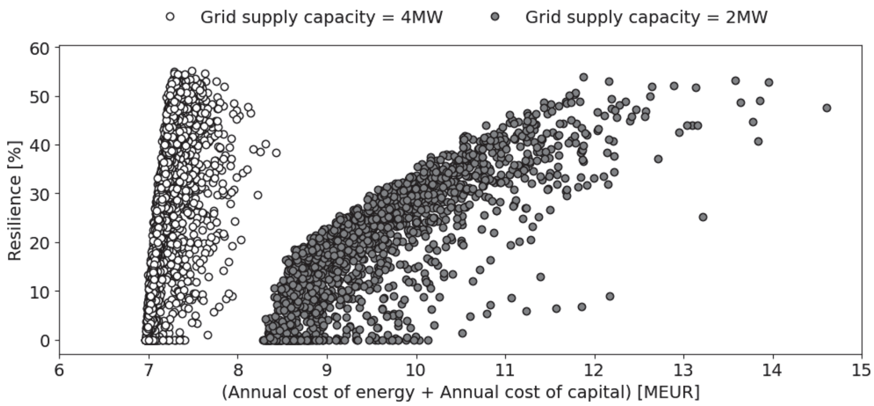

Figure 7: Tradeoff between annual cost and resilience for two different grid supply capacities

combinations of frequency and magnitude can generate any possible disruption profile. Frequency of disruptions can range between 0 and 100%, where 0% corresponds to complete absence of disruptions and 100% represents disruptions occurring at each and every time instance of the week-long evaluation window. The entire analysis presented in sections 3.1-3.3 was done for zero disruptions in the electricity supply. This condition is now alleviated, and frequency of disruptions becomes a variable to the GA-based sizing optimization. Magnitude of disruptions also ranges between 0 and 100%, where 0% represents absence of disruptions and 100% corresponds to a designated maximum magnitude. To resemble the arbitrary nature of supply disruptions, a random variation is selected for the value of disruption magnitude at each instance of occurrence. A system designed to react to a specific disruption profile, is a system with corresponding level of resilience. A resilience index is derived as $Resilience\ \% = Frequence\ of\ disruptions\ \% \cdot Average\ magnitude\ of\ disruptions\ \%$.
The co-optimization algorithm is adapted so that the GA-based sizing runs for two objectives, annual cost, and resilience. In this way, tradeoffs between cost reduction and resilience enhancement can be revealed. To capture the effect of grid supply capacity, two scenarios are compared: one with a maximum surplus capacity of 4MW (same as in sections 3.1-3.3) and one with a capacity closer to today's levels, namely 2MW. The maximum magnitude of disruptions is kept consistent at 2MW to enable direct comparison between the two scenarios. It is noted that grid capacities below 2MW yield mostly non-converging operational solutions. The feature of random restart was tested from the aspect of dampening the impact of randomized magnitudes on annual cost and resilience index, but the accrued deviations were lower than 0.1%. Therefore, no random restart is utilized to keep the computational overhead of co-optimization at acceptable levels. A population size of 100 individuals along with 50 generations were selected to secure convergence in the solution of the GA.

The entire set of converged individual solutions and the accrued Pareto fronts are illustrated in **Fig. 7**. Resilient index ranges between 0 and approximately 55% in both scenarios. Overall annual costs are shifted to the direction of increase for the 2MW scenario. More importantly, the cost increasing resilience from 0% to 55% is considerably varied: for the 4MW scenario, annual cost shall be increased by 4.7% to elevate resilience to 55%. But for the 2MW scenario, the cost of identical increase in resilience is 42.8% higher than the baseline. Optimal sizing of resilient systems for both 4MW and 2MW scenarios is provided in **Table 5**, And corresponding operational profiles are presented in **Fig. 8.a** and **Fig. 8.b**, respectively. The accrued grid capacity profile including supply disruptions is superimposed as dotted line. For the 4MW scenario, the importance of battery remains significant, whilst slight contributions from the fuel cell rise during instances of high demand. However, in the 2MW scenario, fuel cell has a significant role in compensating for disruptions in grid supply. Therefore, in the absence of a stable power grid, a robust hydrogen supply grid is essential to provide in the

Table 5: Optimal sizing for resilient energy system under two different grid capacity scenarios

Grid cap. [MW]	Battery [MWh]	Electrolyzer [MW]	Fuel cell [MW]	CGH2 tank [kg]	LH2 tank [kg]	Compressor [kg/h]	Liq. plant [kg/h]
4	48	2.7	0.8	700	1400	32	16
2	120	6.5	5.5	2000	4000	104	33

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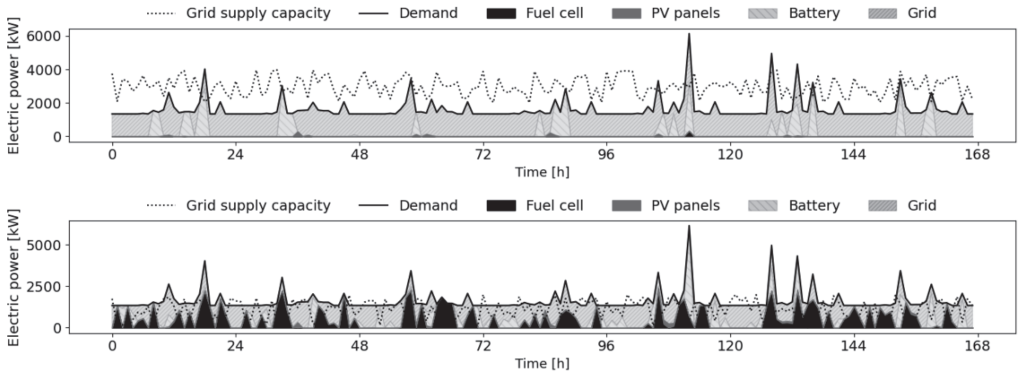

Figure 8: Optimal operation for resilient systems under two grid capacities: (a) 4MW; (b) 2MW

conversion process through the fuel cell. Of course, green hydrogen, even if it is externally supplied, shall be produced by green electricity. It shall be noted that airports, at least based on today's business operation, rely heavily on subsidized services. Therefore, scenarios involving dedicated production of hydrogen or exclusive power purchase agreements present high possibilities for the future.

Overall, it is concluded that the development of resilient energy systems shall be accompanied by simultaneous increase in the capacity of regional grids. Results shown in this study are case specific; nevertheless, demand and supply profiles present high diversity which covers a wide range of potential variations in similar-scale energy systems. Relative tradeoffs between resilience and cost can also be generalized to systems with equivalent supply-demand lapses. Future studies can explore alternative demand and supply profiles, as well as alternative layouts for the energy system.

4 CONCLUSIONS

The operational and sizing co-optimization of an airport energy hub has been presented. A linear mathematical representation has been developed for a hybrid system that powers ground and airborne consumers of electricity and hydrogen, whilst connected to the grid. Operational scheduling has been done through a mixed integer linear programming optimizer and sizing optimization through a genetic algorithm. The objective of co-optimization has been the summary of annual cost of energy and capital.

It has been shown that on-site production of liquid hydrogen is not practically viable due to limitations in electricity grid supply capacity. Instead, external supply has been suggested. Electricity flows have taken approximately 58% of the annual cost of energy whilst battery acquisition cost has dominated the overall cost of investment with a 60% share. The inherent uncertainty in market parameters, namely electricity price, compressed and liquid hydrogen price, as well as interest rate yielded a coefficient of variation of approximately 17% in the annual cost. Monte Carlo simulation and Sobol sensitivity analysis identified electricity prices as the main contributor to uncertainty with a share of approximately 82% over the rest uncertain parameters.

A probabilistic approach to resilience has been introduced, based on the introduction of disruptions on electricity grid supply capacity. Resilience has been added to the co-optimization objectives, yielding system layouts that can react to disruptions. It has been shown that for a system with today's grid capacity of 2MW, increasing resilience from 0 to 55% implies a cost penalty of approximately 43%. In the case of a future increase in grid capacity to 4MW, cost of resilience has been estimated at less than 5%. This work has shown that concurrent developments are needed, both in the sizing and operation of future hybrid systems as well as the capacity of power grids. These developments together can render resilient and environmentally friendly airport hubs, integrated in a sustainable energy ecosystem.

NOMENCLATURE

CGH2	compressed gas hydrogen
CO2	carbon dioxide
COV	coefficient of variation (%)
GA	genetic algorithm
LH2	liquid hydrogen
LTO	landing and takeoff
MILP	mixed integer linear programming
PV	photovoltaic
SAF	sustainable aviation fuel
SOC	state of charge (%)

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