OPTIMISING THE ENERGY SYSTEM FOR ELECTRIFIED AIRPORT OPERATIONS USING DIGITAL TWIN

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***Abstract*—This paper describes a general layout of electric infrastructures to implement a Digital Twin for the conversion of actual airports into the electric aviation era. The proposed Digital Twin allows to test different electricity management strategies to maximize the chosen target whether it is saving electricity costs or reducing CO2 emissions, focusing on the feasibility of new airport infrastructures in northern countries.**

Keywords—digital twin, airports, electric aviation, electric vehicles, energy management

I. INTRODUCTION

The technical progress of electric aviation is rapidly advancing. Within the coming five-year period several models of regional electric aircraft will be on the market. Since electric aircraft does not produce any operational greenhouse gas emissions (if the electricity is produced with renewable energy), it is set to be one of the most climate-efficient modes of transport in the future. At the same time, electric operation means drastically reduced fuel and maintenance costs, which creates very competitive operating costs and thus potential for a completely new regional air system [1]. Regional flights are considered the optimal target for the use of electric aircraft due to the actual technology limitation of the lithium battery size, which doesn't allow yet to perform longer trips .

A. Background

In 2020 the aircraft producer company Pipistrel obtained the first certification for a fully electrified aircraft from EASA [2], and for 2027 the first electric aircraft for commercial routes will be available. Hybrid aircraft are also playing a crucial role in this process because they represent the link between fossil fuel aircraft and fully electric, since they combine the range of classic aircraft with lower emissions of electric motor. Hydrogen aircraft are still under research but in the next decades they can represent the state of art of aviation [3]. The airports interested in this electric revolution need a new layout of electricity management, because the current infrastructure capacity is not enough to guarantee a suitable electric supply.

Northern countries are collaborating to promote electric aviation with the purpose of improving their mutual connectivity [4].

One aspect to consider in this electric revolution is the airports' infrastructure capacity. The planning of suitable electric equipment represents an opportunity to increase the appeal of minor airports, especially for regional flights.

B. Infrastructure layout proposed

Instead of a massive renovation of the existing infrastructure, the possibility of adding new infrastructure is investigated in this paper rationalizing and regulating the electricity usage. Besides the actual grid, it is considered to add solar farm, energy storage system (i.e. ESS), electrolyzer for production hydrogen and fuel cell to convert hydrogen to electricity. Each of those elements can be added or removed from the layout, or operate just under certain conditions (i.e. electricity price or solar farm production surplus). The benefits of this approach are multiple: peak shaving to avoid grid instability and electric blackouts during electric aircraft charging, renewable energy storage, energy availability for fast charge stations, possibility to switch to island mode in case of grid blackout. In this paper, it will be highlighted the importance of using a high-time Digital Twin of the airport to design the new configuration for an electrified airport, focusing on pros and cons of different management strategies.

C. Case study: Tampere-Pirkkala airport

This paper takes in consideration the airport of Tampere-Pirkkala (IATA: *TMP*, ICAO: EFTP), located in Pirkanmaa (Finland). The carrier airBaltic is the main operator, which is using this airport as a spoke for its hub in Riga. Tampere-Pirkkala airport is a typical example of northern countries′

airport, based on regional market and a perfect candidate to develop the electrification of aviation. Fig. 1 shows the aerodrome chart and Fig. 2 shows the passengers traffic of the airport.

In 2022 the airlines airBaltic, Finnair and Ryanair operated regularly in this airport. The aircraft used by those airlines are shown in Table I. The case study is focused on the temporal horizon 2030-2040, with the hypothesis that electric aircraft is a developed technology for regional travels and hybrid technology is used for longer routes.

TABLE I. AIRCRAFT MAJOR FEATURES

Airline	**aircraft info**		
	Model	***Seats***	***Destination***
airBaltic	A200-300	145	Riga, seasonal others
Finnair	ATR-72	72	Helsinki
Ryanair	B737-800	180	London

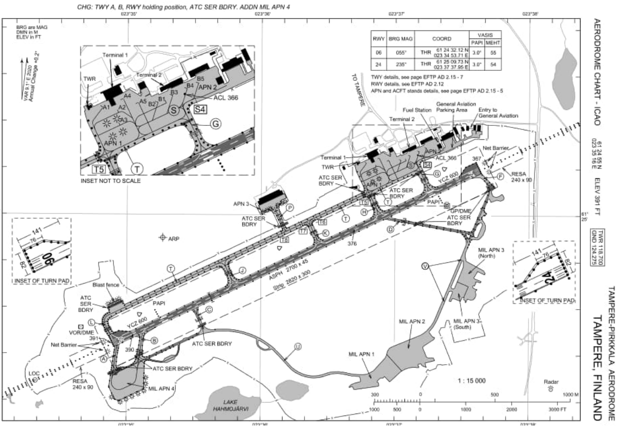

Fig. 1 Tampere-Pirkkala aerodrome chart (ICAO)

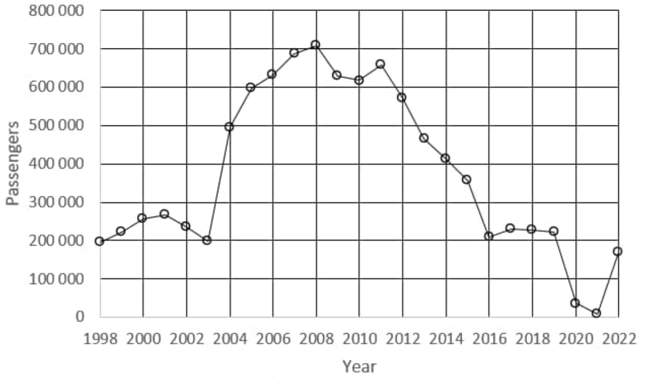

Fig. 2 Annual passenger traffic at TMP airport (data from Finavia)

II. METHODS

Digital Twin describes the energy flow considering the flight schedule and the solar farm productivity. The minute time resolution allows you to overview and predict failures with remarkable precision.

A. Model

The energy flow of the layout is built with energy balance equations starting from the amount of energy needed for charging aircraft. At each timestep, that amount of energy is taken from the source or storage which suits better the user's management strategy. If solar farm produces enough energy, the overproduction is stored or sold to the grid, otherwise if it is needed more energy, it is taken from the grid. The general equation of the flow is described in (1).

$$E_{sol} + DE_{grid} = E_{airp} + DE_{ESS} + E_e + E_h + E_{airc} \quad (1)$$

Where E_{sol} is the electricity produced with the solar farm, DE_{grid} is the net electricity exchange form/to the grid, E_{airp} is the electricity consumption of the airport facility, DE_{ESS} is the net energy balance of ESS, E_e is the electricity used in the electrolizer to produce hydrogen, E_h is the amount of energy stored as hydrogen, E_{airc} is the electricity used to charge the aircraft or other EV (i.e. Electric Vehicles).

Fig. 3 shows the energy flow of the model. Note that the flow can be bidirectional (e.g. between ESS and grid), depending on the management strategy adopted.

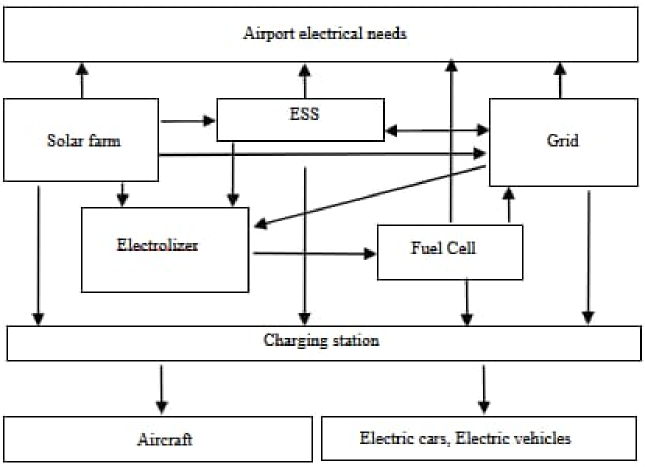

Fig. 3 Energy flow caption

After a general review of the different technologies, as ESS is taken in consideration lithium battery, because it represents a plausible solution for the electrification of aviation [5]. In this study EV fast charging stations infrastructure with integrated battery is applied [6]. This layout is widely suggested to lower the peak request and can be easily adopted either for aircraft or for electric cars or other vehicles. This approach allows us to investigate the possibility of creating a logistic center where EV can be charged, strengthening in this way the appeal of the airport.

The model describes the SOC (i.e. State Of Charge) of the ESS and the SOC of the aircraft´s battery (2). This value is a measurement of the amount of energy available in a battery at a specific point in time expressed as a percentage.

$$SOC= E*P_{nom}/100 \quad (2)$$

Where E is the energy stored and P_{nom} (kWh) is the nominal battery capacity.
In case of values under preset SOC_{min}, no energy can be drained from the ESS, instead ESS and aircraft's battery are full over SOC_{max} (typically 100), so they cannot accumulate more energy. Those two values are important to switch the different managing strategies.

ESS is considered as lithium technology battery with fast charge system. This system is developed to reduce the charging time considering the durability of the battery and preserve it. For this reason, the speed of charge increases linearly from an initial value, then reaches the maximum and in the end decreases proportionally with the SOC [7].

From the amount of energy used in each step, the model also gives the amount of CO2 emissions produced and expenses for electricity supply, based on official data given from Fingrid, Finnish electricity transmission system operator.

B. Data considered and calculations

Digital Twin can accomplish different purposes based on the user's needs [8]. In this paper the Digital Twin is used as simulation model of a non-existed object (future infrastructures) and as simulation model fed with real data: weather conditions, electricity price, CO2 emission factor in Finland. All the configurations are made to work with the internet of things (IoT), so in the future it can work with real time data as an adaptive Digital Twin with the possibility to upgrade the system with machine learning features.

In this paper is taken in consideration the year 2022, because of the availability of data for the full year from all the sources. The data has been reduced to minute resolution, from the original format using different approaches, as shown in Table II.

TABLE II. DATA HANDLING

Data	**Data handling to achieve minute resolution**		
	Source	***Original format***	***Method***
Airport electricity consumption	FINAVIA	Hour	Hour value divided by 60
Solar radiation	Lemene Oy	Hour	Value kept
Electricity production	Lemene Oy	Hour	Hour value divided by 60
Emission factor	Fingrid	3 minutes	Values interpolated linearly to minute resolution
Electricity cost	Fingrid	3 minutes	Values interpolated linearly to minute resolution

1) Airport current and future power need

As shown in Table I, three different commercial aircraft are flying through this airport. Table V. shows the actual arrival timetable.

TABLE III. COMMERCIAL AIRCRAFT ARRIVAL SCHEDULE: A=A220-300, B=ATR-72 and C=B737-800

Time	**Aircraft arrivals**						
	Mon	Tue	Wed	Thu	Fri	Sat	Sun
0:35	A	A	A	A	A	A	
0:40	B	B	B	B	B	B	
0:45	A						
11:25				A			
11:35		C					
12:15			A		A		
12:45	A						
13:40							A
16:20	A	A	A		A	A	
18:35						C	
22:35		A		A		A	
23:00			A				
23:20	A						

In our future scenarios the equivalent electric/hybrid aircraft are available to charge just after arrival. Based on the actual technology and expectations of its development, we assume that the aircraft can be replaced with the ones showed in table IV:

TABLE IV. FUTURE AIRCRAFT FEATURES

Aircraft	**Replacement**		
	Aircraft	***Technology***	***Battery size (kWh)***
A220-300	"Hybrid plane"	Hybrid (20 % electric flight)	500
ATR-72	"Full electric plane"	Electric	2000
BOEING 737-800	"Hybrid plane"	Hybrid (15 % electric flight)	600

In the future scenario we consider that fast charge technology has developed enough to guarantee 750 kW of maximum power, as shown in Fig. 4:

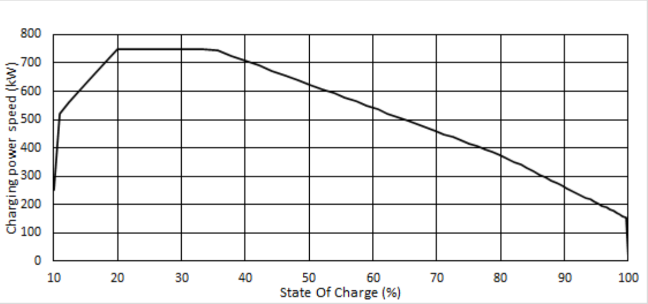

Fig. 4 Fast charge speed profile considered

An example for two days of the total power needed to guarantee the correct functioning of the electric infrastructure is shown in Fig. 5.

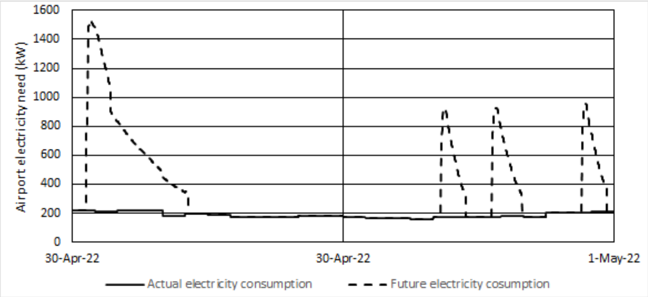

Fig. 5 Airport actual electricity consumption and future scenario electricity consumption

The power needed to charge commercial electric aircraft adds peaks to the airport base electricity consumption. If the grid cannot handle the increased power demand, the option that we should consider is peak shaving, for example with solar farm and ESS.

2) *Solar farm model*

Solar farm has two options for data feeding: real data from Lempäälän Energia Oy (abbr. Lemene), with two solar farms of 2MWp, situated 12 km from the airport [9], or production estimated from solar radiation model from (3).

$$El_{prod}=Rad_t /60/1000*kW_p*(1-loss) \tag{3}$$

Where El_{prod} (kWh) is the electricity produced, Rad_t (W/m^2) is the solar radiation coming to a tilted solar panel, kWp (kW) is the nominal power of the solar farm and loss (/) is a fraction which considers the total electrical losses in the solar farm. The coefficient 60 are minutes per hour and the coefficient 1000 (W/m^2) is the test radiation to determine the nominal power of solar panels. One-week results is showed in Fig.6.

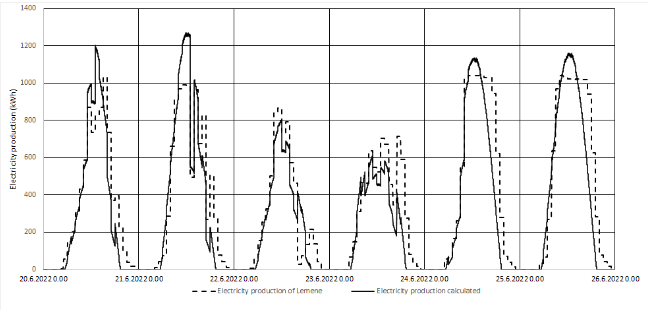

Fig. 6 Production measured and calculated

The solar radiation is calculated in minute time resolution using the methodology proposed by Duffie and Beckman, 2013 [10]. The first step is calculating the exo-atmospheric radiation, which depends only on physical parameters, then the effective radiation is obtained with (4).

$$Rad_t=Rad_{exo} * k_t \tag{4}$$

Where Rad_t (W/m^2) is the solar radiation coming to a tilted solar panel, Rad_{exo} (W/m^2) is the exo-atmospheric solar radiation coming to a surface with the same geometry and relative position of the solar panel and k_t is the sky factor representing the reduction of solar energy through the passage into the atmosphere. There are different approaches to determine this factor. We use (5), as proposed by Senese et. al [11] because we have available data of solar radiation measured data from Lemene. We assume that the weather conditions are the same for the whole hour when the radiation is measured.

$$k_t=Rad_{hmeas}/Rad_{exoh} \tag{5}$$

Where Rad_{hmeas} is the horizontal solar radiation measured at one hour and Rad_{exoh} is the horizontal exo-atmospheric radiation calculated in the same hour.

Fig.7 shows the trend of solar radiation simulated and measures the day 26.6.2022 from 17:00 to 18:00. The measured value is not catching the variability of the radiation during the whole hour. One-week results are showed in Fig.8.

In the simulation the surface of solar panels is oriented toward south with a slope of 30 °. Those values correspond to Lemene solar farm and are also an average value between the optimal monthly module inclination angles from the horizontal proposed for Tampere area by Lobera et al, 2013 [12], considering the sunniest period between April to August. The size of the solar farm considered is 2 MW.

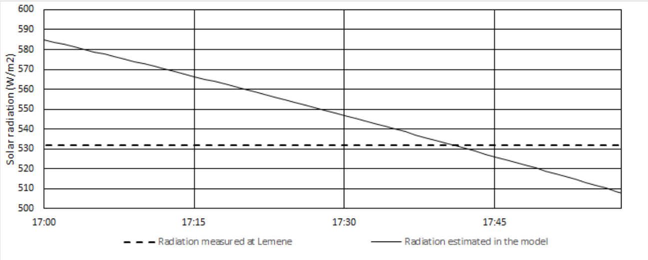

Fig. 7 Comparison between hourly solar radiation measured in Lemene and solar radiation estimated in minute time resolution

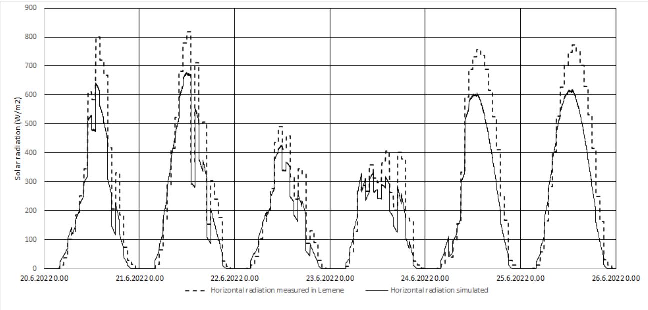

Fig. 8 Comparison between horizontal solar radiation measured in Lempäälä Energia Oy PV1 and horizontal solar radiation estimated

TABLE V. SOLAR MODEL PARAMETERS

Parameter	**Solar radiation**	
	Description	***Value***
lat	Airport latitude	61 24 55 N
long	Airport longitude	023 35 16 E
s	Solar panel tilt	30
a	Solar panel aspect	0

3) *ESS*

We assume that the lithium battery can store all the needed energy, and the C-rate is enough high to permit the feeding of the fast chargers, or we use some other technology (i.e. flywheels, superconductors) alongside ESS.

4) *Electrolyser and fuel cell*

Electrolyser and fuel cell are described as general devices, where electricity its used to create hydrogen (6) and when hydrogen is used in fuel cell to produce electricity (7).

$$Kg_h = E * conv_{EH} * n_{EH} \tag{6}$$

$$E = Kg_h / conv_{EH} * n_{HE} \tag{7}$$

Where $conv_{EH}$ is the energy needed to create 1 kg of hydrogen (39.4 kWh/Kg_H), n_{EH} and n_{HE} are the efficiency respectively of electrolyser and fuel cell. Their values are shown in table VI.

TABLE VI. EFFICIENCY VALUES USED

	Efficiency	
Electrolyser	n_{EH}	0.65
Fuel Cell	n_{HE}	0.55

The efficiency values considered are referred just to the electricity transformation. In this paper, the benefit of using excess processed heat from the system is not analyzed, but it should be considered in a real planning phase.

5) *Emissions and costs calculation*

The emissions of the system described are calculated with (8).

$$Em(t) = E_{grid}(t) * Em_{fact}(t) \tag{8}$$

Where Em are the emissions produced at the timestep t (gCO2), E_{grid} is the amount of energy taken from the grid at timestep t (kWh) and Em_{fact} is the emission factor of electricity consumed in Finland (gCO2/kWh), showed in Fig.9.

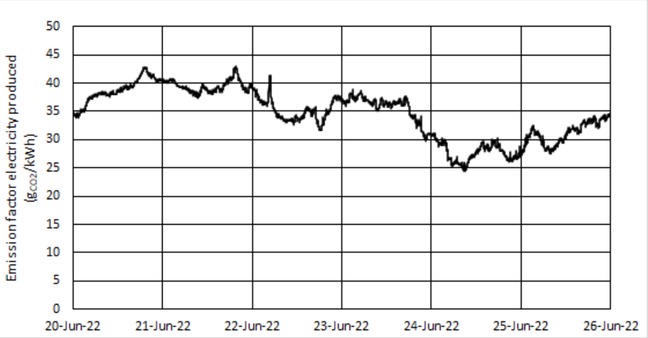

Fig. 9 Emission factor trend

In an equivalent way the cost of the electricity taken from the grid is calculated (9).

$$Cost(t) = Egrid(t) * Price_{el}(t) \tag{9}$$

Where Cost is the electricity cost at the timestep t (€), E_{grid} is the amount of energy taken from the grid at timestep t (kWh) and $Price_{el}$ is the price of energy taken from the grid at timestep t (€/kWh) showed in Fig.10.

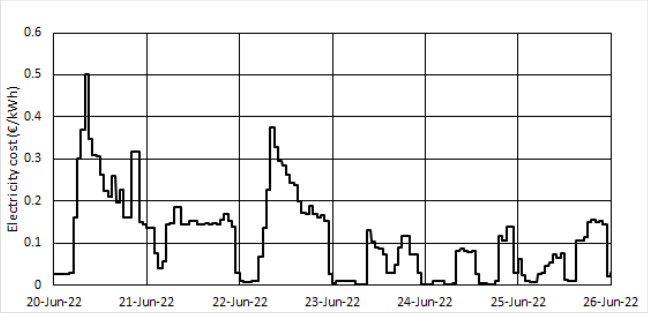

Fig. 10 Energy price trend

The emission factor and price of electricity are taken from Fingrid website [13].

The amount of electricity taken from the grid depends on the airport instantaneous needs, the solar farm production, ESS, and fuel cell management.

III. RESULT AND DISCUSSION

The model has been run with different parameters setting, to verify the solidity and the capacity of simulate different scenarios.

A. *Overall results*

The most interesting results were about the different strategies to manage the energy flow in the airport area. Based on that, different layouts are designed with pros and cons. In Table VII are listed the most interesting considerations from the results obtained, from the simplest layer to the most complex ones.

TABLE VII. OVERALL RESULTS

Strategy	**Scenario**		
	Layout features	***Pro***	***Cons***
No ESS	Solar farm	Simple layout.	No influence to supply when solar farm is not producing.
ESS	Solar farm ESS	Storage of solar farm production.	If the battery becomes full, there is no possibility of further storage.
Electrolysis	Solar farm ESS Electrolysis	Possibility of conversion of overproduction in hydrogen.	High losses. Additional safety requirements.
Fuel cell	Solar farm ESS Electrolysis Fuel Cell	Hydrogen can be used as an energy vector to produce electricity.	High losses. Additional safety requirements.

The model represents a high time resolution energy flow system, with the possibility of managing different operative scenarios. The user can optimize the management strategy based on the prearranged targets. The 3D model allows to have a detailed and realistic rendering of the spaces in the airport area to verify the effective reliability of the schedule taken in consideration.

B. *Solar farm*

The solar farm model reproduces with accuracy the electricity production, as shown in Fig.6. In variables, partially cloudy days the sky factor lays a key role, and it is difficult to simulate its variability. In the future, the connection with pyranometers or other weather devices will improve the forecast's precision. In addition, real-time electrical production data will help improve the model algorithm.

In this case study, the site coordinates are 61°24'32.99" N 23°35'9.59" E. At this latitude, the solar radiation varies significantly during the year: spring and summer (from April to September) gives the 85% of yearly total solar energy, instead in autumn and winter (from October to March) is delivered just the 15%. Considering the data analyzed from the solar farm of Lemene, the electrical production follows the same pattern. This fact raises the question of how to size the solar farm and what role it plays in a year around flight schedule, with the possibility of introducing other electricity sources.

C. *ESS manager*

The key component of the model is the ESS. The battery operates as a buffer and the correct dimension of it guarantee a smooth functioning of the airport. Fig. 11 shows the different behavior of three different ESS size options.

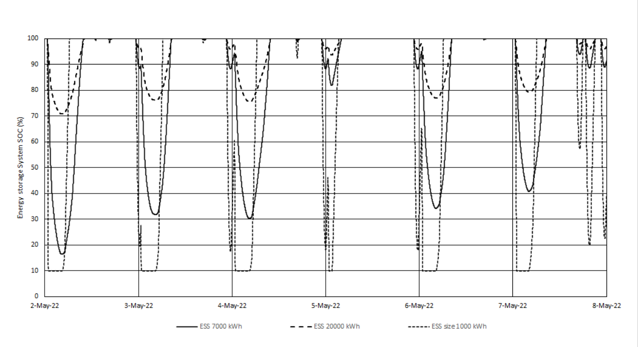

Fig. 11 ESS dimension comparison

The ESS size of 7000 kWh results to is the best choice for the case study because on cloudy days it has enough energy stored and the inertia is enough fast to charge at 100% on sunny days or when electricity is cheap. A bigger size of 20000 kWh is over dimensioned, with the risk of making a huge investment in storage that works almost all the time near the maximum capacity. The option of 1000 kWh is not to be considered because the ESS goes empty daily for the most time of the year and so it cannot shave the peak energy request.

Focusing on the effects of ESS on the grid supply, we observe that it shaves the electricity demand when the amount of energy required is impulsive (Fig. 12). In this case, because the solar farm cannot provide enough energy, the battery supplies it and, in the end, if still energy is needed, the grid itself. In the case of power available from the grid and electricity price smaller than a target value (i.e. 0.01 €/kWh), the ESS purchases the energy from the grid. The plateau in the figure corresponds to the maximum power allowed from the grid.

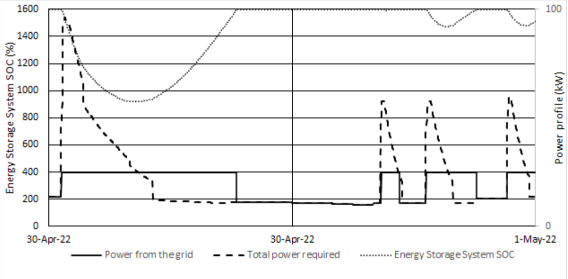

Fig. 12 Shaving of power needed

D. *Electrolisys and Fuel Cell*

We investigated the chance to use the overproduction of solar farm electricity to create hydrogen and convert it into electricity in case of necessity. The scenario is winter season, the battery charges with solar energy and with electricity from the grid if the price is under a threshold value. As shown in Fig. 13, on 23rd of January the ESS is full, and because of a sunny day the solar farm overproduces electricity, which is converted into hydrogen. On 24th of January hydrogen is used to charge the aircraft because the battery goes empty. On the following days, the solar farm, ESS, and the grid provide enough energy to supply the charging needs.

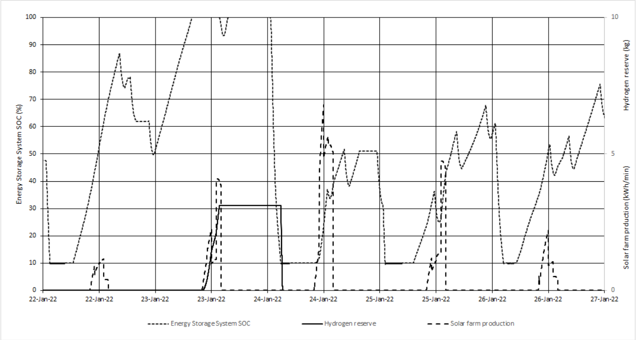

Fig. 13 Analysis of electrolysis and fuel cell adoption

E. Aircraft charging time

The use of speed charge model permits us to check the charging time of the electric aircraft. Table VIII shows the charging time calculated using the fast charge with maximum speed power 750 kW. The resulting charging time from 10 % to 100 % is considerable and not practical for the actual airport's procedures, the option from 20 % to 80 % is more feasible for a regional airport like Pirkkala-Tampere airport. However, in the future it is desirable a fastest charging technology to maintain the same aircraft checking and refueling routine as today.

TABLE VIII. ELECTRIC/HYBRID AICRAFT CHARGING TIME

	Battery size (kWh)	**Aircraft charging time (hh:mm)**	
		From 10 % to 100 %	***From 20 % to 80 %***
Hybrid	500	1:07	0:34
Electric	2000	4:28	1:49
Hybrid	600	1:21	0:41

F. Comparision with fossil fuel aircraft

The model permits a comparison between actual fossil fuel aircraft and a full electric one of the same category (TABLE IX).

ATR-72 is a suitable candidate for this topic. Its technical features are available in [14].

TABLE IX. FOSSIL FUEL AND ELECTRIC AICRAFT COMPARISION

	Aircraft values		
	Passengers	***Route***	***CO2 emissions***
ATR-72	72	200 NM	1970 kg
Electric 2 MW	70	200 NM	120 kg

The comparison is made with electricity from the grid. The emissions made for a full electric travel are about 20 times less than normal fossil fuel aircraft. If the electricity is produced from solar farm, the related emissions are equal to zero. The hybrid technology is reducing the emissions depending on the percentage of hybridization, but of course less than a full electric aircraft. In this paper those emissions are not calculated because of the lack of solid design data of hybrid aircraft.

G. 3D rendering

The rendering software gave an extraordinary graphical output of the scenarios considered. The high-resolution graphic and the different camera option permitted deep positioning considerations, based also on daily or seasonal light alternation, as shown in Fig. 14 and Fig. 15.

Fig. 14 Rendering of TMP airport

Fig. 15 Rendering of TMP airport

IV. CONCLUSIONS

The digital twin model works close enough to the real world and can simulate various kinds of scenarios for future electric infrastructure development, including energy production and storing, besides charging electric aircraft and other EVs. The Digital Twin is also a reliable tool to plan and optimize the energy flow of the airport or similar facilities. Electrolysis and Fuel Cell technology will be investigated more deeply, and more complex strategies will be implemented to use hydrogen as a buffer for the energy system. The plan to upgrade this digital twin is to connect real-time data, starting from public information like weather conditions, energy price and emission factors. As soon as infrastructures are built, they will be also connected to the digital twin. For example, the solar farm is in the planning phase and will be placed in June 2023, so in summer 2023 local real time data will be implemented in the digital twin.

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