Electronic Supplementary Information. Unravelling the potential of Sustainable Aviation Fuels to decarbonise the aviation sector.

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A Radiation profiles

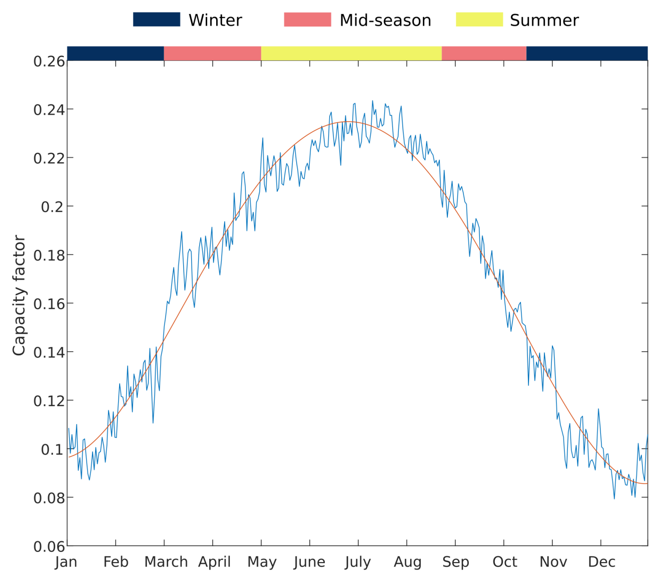


Figure A.1: Average annual capacity factor of solar radiation in Spain over the period 2010-2019 and seasons defined in the RTN model.

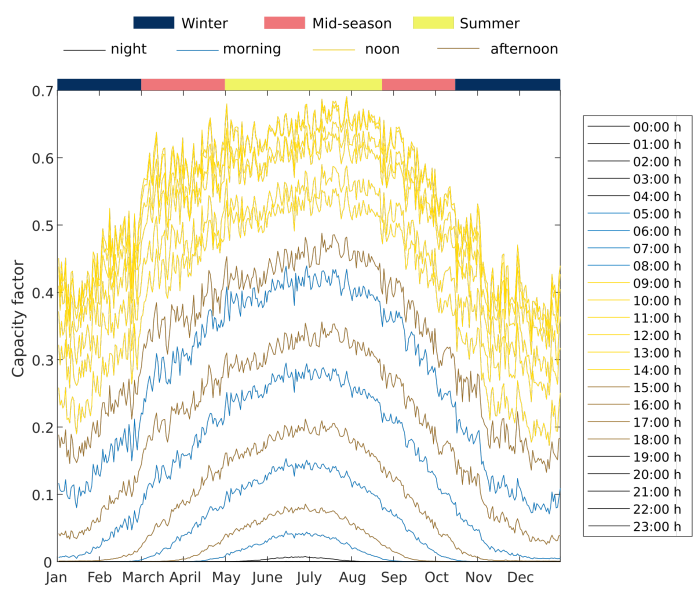


Figure A.2: Hourly capacity factors across the year over the period 2010-2019 and seasons defined in the RTN model.

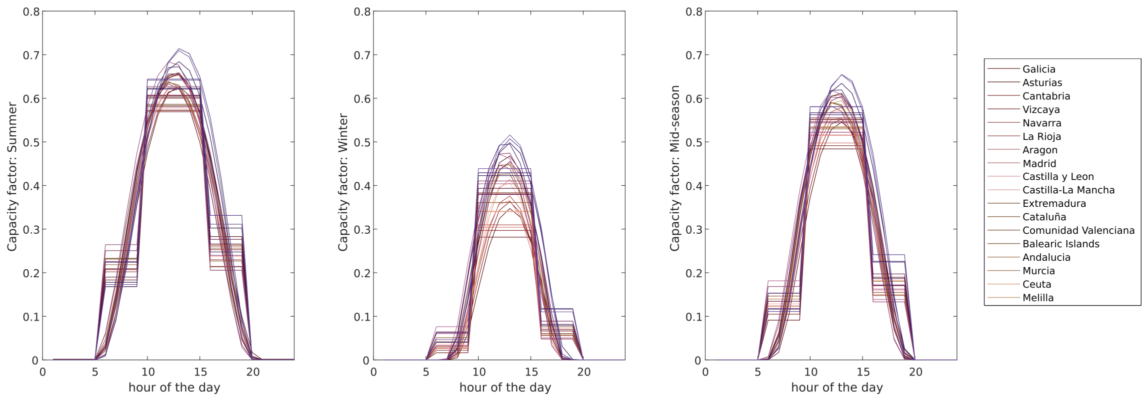


Figure A.3: Capacity factor profiles for the 18 NUTS regions of Spain and adjustment to the temporal resolution of the RTN model.

B Demand profile

Fig. B.1 shows the annual number of operations per airport in Spain. Total demand of jet fuel was allocated to each airport according to the relative number of operations. For daily consumption, it was assumed that 85% of the demand was evenly fulfilled across the morning, noon, and afternoon periods while the remaining 15% was fulfilled during the night period.[1,2]

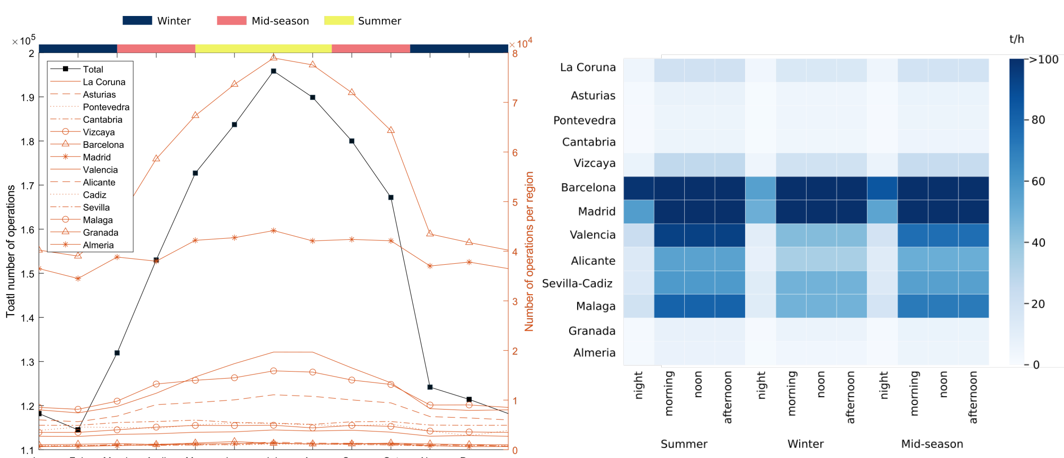


Figure B.1: Number of operations per airport in Spain included in the RTN model and profile of the RTN model.

C Airports used to define the minimum regional demand of jet fuel

Table 1: Airports used to define the minimum regional demand of Jet Fuel in the RTN model.[1,2]

Airport	Operations	Passengers	Status
ADOLFO SUÁREZ MADRID-BARAJAS	387,568	53,400,844	Included
BARCELONA-EL PRAT	323,535	47,284,346	Included
PALMA DE MALLORCA	208,788	27,970,656	Included - Balearic Islands
MALAGA-COSTA DEL SOL	137,178	18,626,581	Included
GRAN CANARIA	118,551	13,092,475	Excluded - Canary Islands
ALICANTE-ELCHE	95,323	13,713,063	Included
IBIZA	75,691	7,903,928	Included - Balearic Islands
TENERIFE SUR	69,846	11,248,882	Excluded - Canary Islands
VALENCIA	68,042	6,745,231	Included
TENERIFE NORTE	61,102	4,706,827	Excluded - Canary Islands
LANZAROTE	59,477	7,388,964	Excluded - Canary Islands
SEVILLA	48,661	5,108,817	Included
JEREZ DE LA FRONTERA	48,627	1,046,549	Included
FUERTEVENTURA	48,216	6,049,291	Excluded - Canary Islands
BILBAO	46,990	4,973,809	Included
MADRID-CUATRO VIENTOS	46,568	3,341	Included
SABADELL	41,261	4,544	Included
MENORCA	30,293	3,434,615	Included - Balearic Islands
SANTIAGO	21,519	2,645,362	Included
GIRONA	19,254	1,946,694	Included
LA PALMA	17,757	1,302,485	Excluded - Canary Islands
A CORUÑA	16,075	1,141,389	Included
REUS	16,023	1,018,889	Included
ASTURIAS	13,005	1,407,217	Included
FGL GRANADA-JAEN	12,539	901,967	Included
VIGO	12,479	1,065,595	Included
SON BONET	12,258	2,159	Excluded
ALMERIA	12,219	1,007,446	Included
SEVE BALLESTEROS-SANTANDER	10,989	937,643	Included
SALAMANCA	10,110	15,030	Excluded
MURCIA-SAN JAVIER	8,616	1,196,587	Included
VITORIA	8,435	84,261	Excluded
ZARAGOZA	7,965	438,035	Excluded
MELILLA	7,957	324,366	Excluded
HUESCA-PIRINEOS	7,758	257	Excluded
CORDOBA	7,756	8,064	Excluded
SAN SEBASTIAN	6,925	281,859	Excluded
PAMPLONA	5,683	165,608	Excluded
VALLADOLID	5,100	227,259	Excluded
EL HIERRO	4,190	199,380	Excluded - Canary Islands
CEUTA /HELIPUERTO	2,521	17,821	Excluded
BURGOS	2,366	5,953	Excluded
LEON	2,236	44,254	Excluded
BADAJOZ	1,865	49,304	Excluded
LA GOMERA	1,854	48,711	Excluded - Canary Islands
LOGROÑO	1,447	20,008	Excluded
ALGECIRAS /HELIPUERTO	1,376	10,570	Excluded
ALBACETE	430	1,380	Excluded

D Accounting of CO_2 emissions

Fig. D.1 shows a scheme for the accounting of CO_2 emissions in the RTN model.

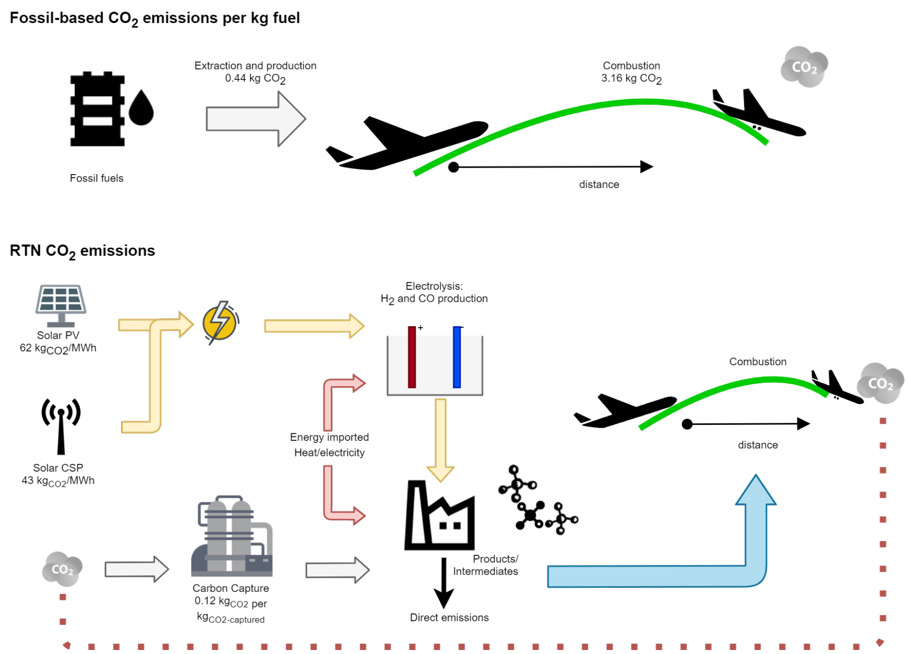


Figure D.1: Lifecycle CO_2 emissions considered in the production of jet fuel.

The values associated to the carbon intensity of solar panels were taken directly from the Ecoinvent database.[3] The infrastructure represents a photovoltaic power plant with a capacity of 570 kWp and a lifetime of 30 years. It consists of a multi-crystalline silicon panel, an open ground mounting structure, an 500 kW inverter (15 y lifetime) and a 570kWp electric installation. The process includes all the components for the installation and the energy used for mounting. Electricity production is 847.5 MWh per year and amortisation assumes an extrapolation of current generation capacities up to the end of life.[4] In the case of CSP, the plant considered in the database has a capacity of 50 MW and lifetime of 30 years. The elements considered include collector field area, thermal storage unit, heat transport fluid system and power block unit.[5]

E Results

Table 2 presents the production costs and CO_2 emissions embedded for all the cases considered. As observed, the unitary production cost of the fuel and CO_2 emissions present a slight reduction as the demand increases. The reason behind this behaviour is that non-scalable technologies (solar PV, AWE, and storage technologies) have the larger contribution toward the indicators and their contributions remain at similar values across the scenarios. At larger production rates, scalable technologies benefit from economies of scale and reduce production costs by a slow margin.

Table 2: Technology constraints and performance indicators for different deployment level of Jet Fuel

	FT			MtF		
	10%	50%	100%	10%	50%	100%
Capacity constraints						
Solar PV (GWh per cell)	2	10	20	2	10	20
AWE (t/h per cell)	20	100	200	20	100	200
Network performance						
Investment (€$*10^9$/y)	4	209	417	5	260	520
Prod. costs (€/kg_{fuel})	5.03	4.97	4.95	3.97	3.91	3.91
Emissions (Mt_{CO2eq}/y)	2	11	23	3	16	32
Emissions (kg_{CO2eq}/kg_{fuel})	2.7	2.7	2.7	2.4	2.4	2.4

E.1 Fischer-Tropsch

Fig. E.1 shows the cost breakdown for the FT route for different demands and annual behaviour of the technologies deployed. Fig. E.2 displays the corresponding network for each scenario.

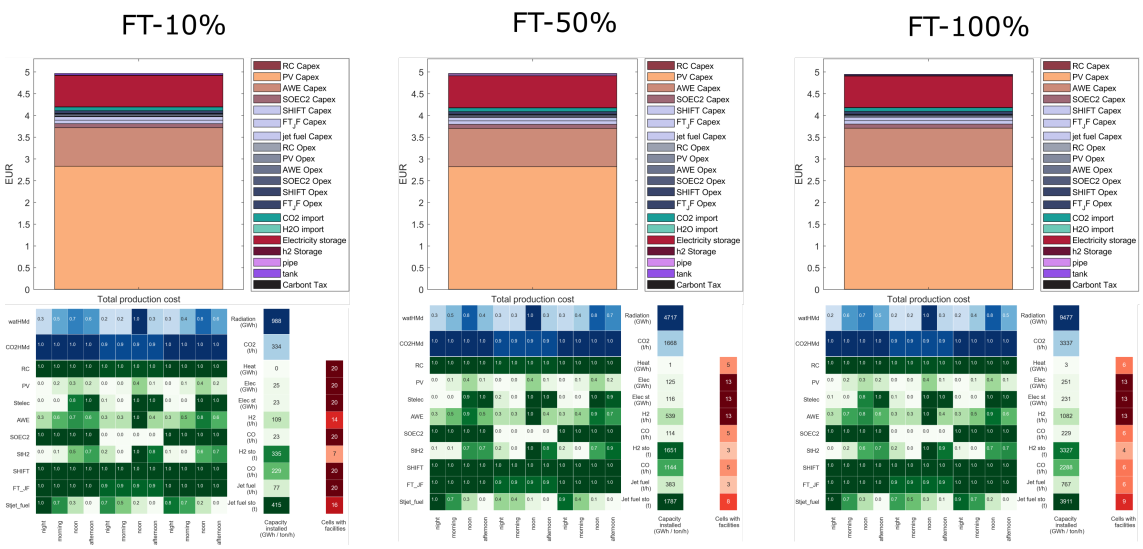


Figure E.1: Costs breakdown and technologies profile at different levels of supply of jet fuel demand for the FT route during the periods defined in the network. The resources (blue) and technologies (green) are shown in the left depicting the hourly behaviour at night, morning, noon, and afternoon for the three different seasons considered (summer, winter, and mid-season). The values shown in each square refer to the production rate in terms of the total capacity installed, which is reported in the middle bar. The red squares report the number of cells within the total space that have installed the corresponding technology.

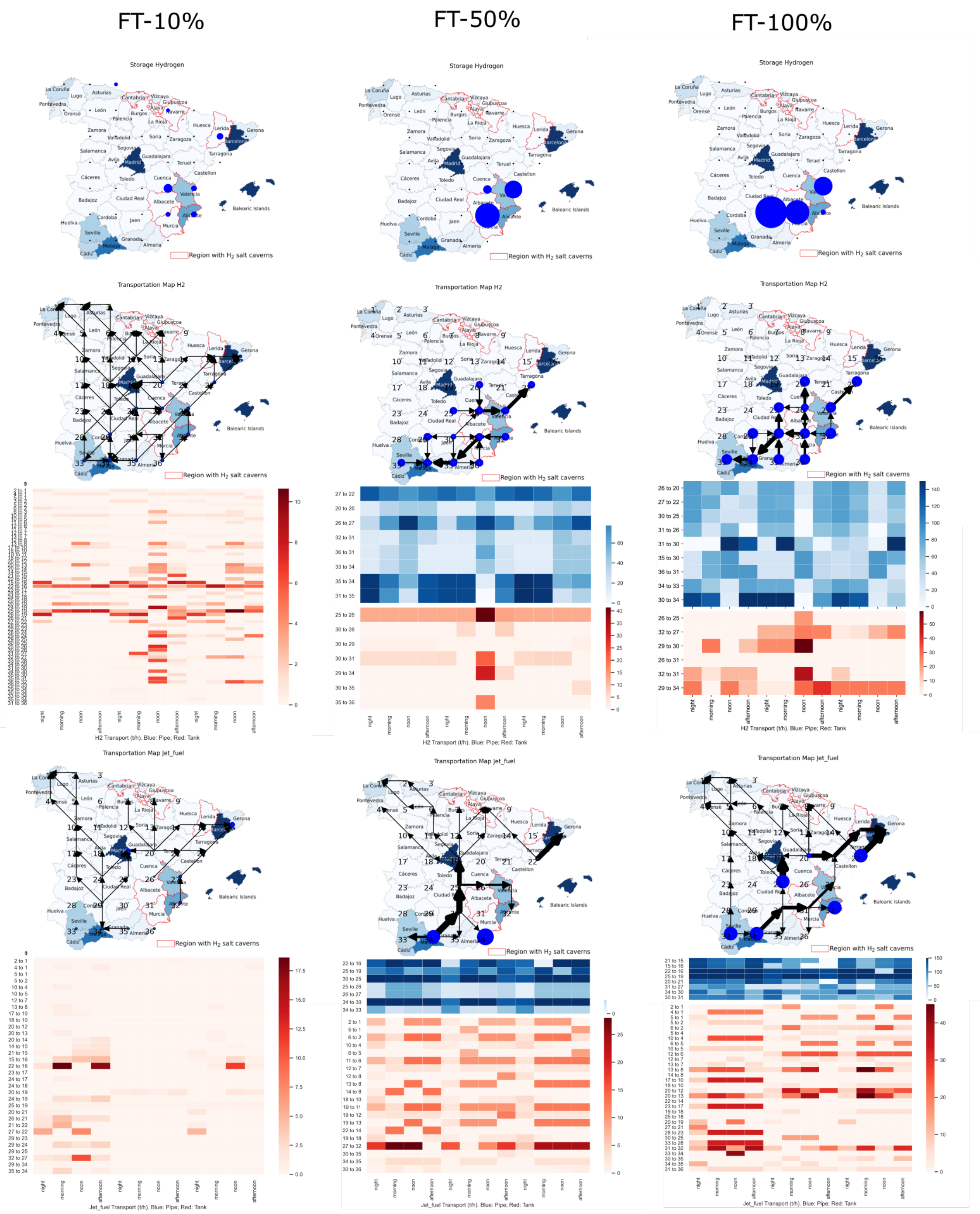


Figure E.2: Network performance at different levels of supply of jet fuel demand for the FT route.

E.2 Methanol to fuels

Fig. E.3 shows the cost breakdown for the MtF route for different demands and annual behaviour of the technologies deployed. Fig. E.4 and E.5 display the corresponding network for each scenario.

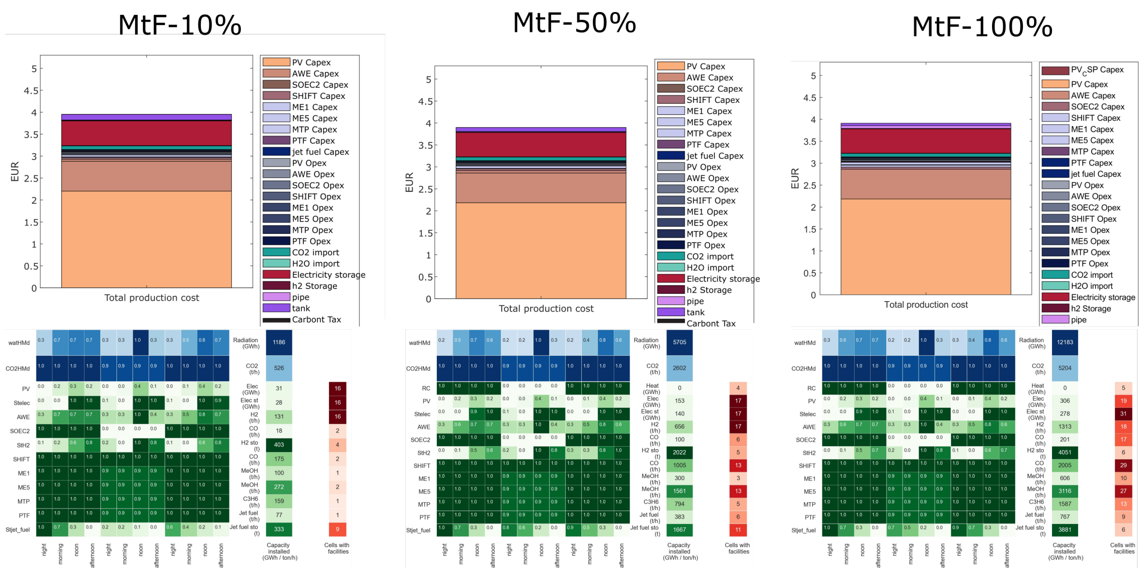


Figure E.3: Costs breakdown and technologies profile at different levels of supply of jet fuel demand for the FT route during the periods defined in the network. The resources (blue) and technologies (green) are shown in the left depicting the hourly behaviour at night, morning, noon, and afternoon for the three different seasons considered (summer, winter, and mid-season). The values shown in each square refer to the production rate in terms of the total capacity installed, which is reported in the middle bar. The red squares report the number of cells within the total space that have installed the corresponding technology.

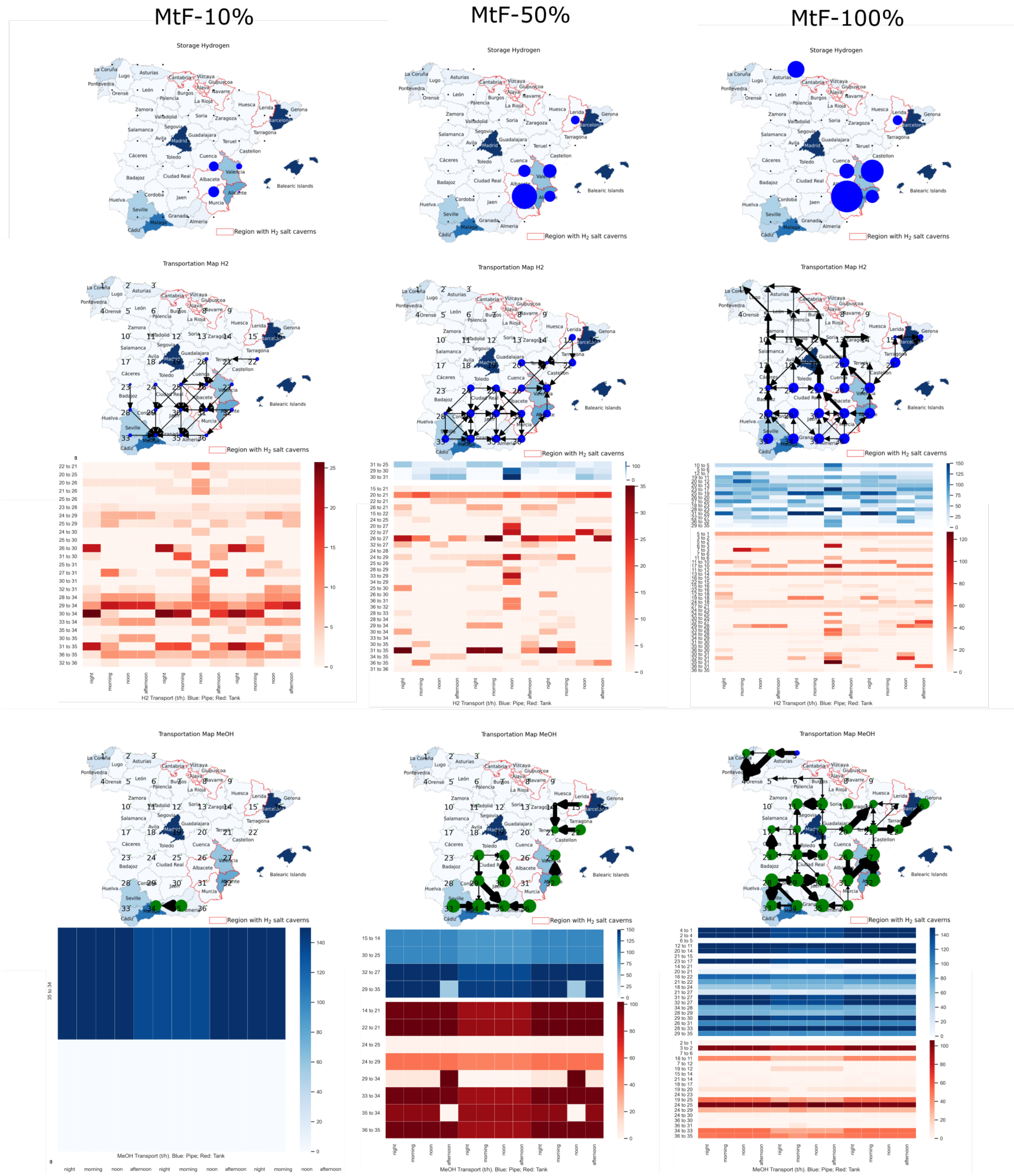


Figure E.4: Network performance at different levels of supply of jet fuel demand for the MtF route.

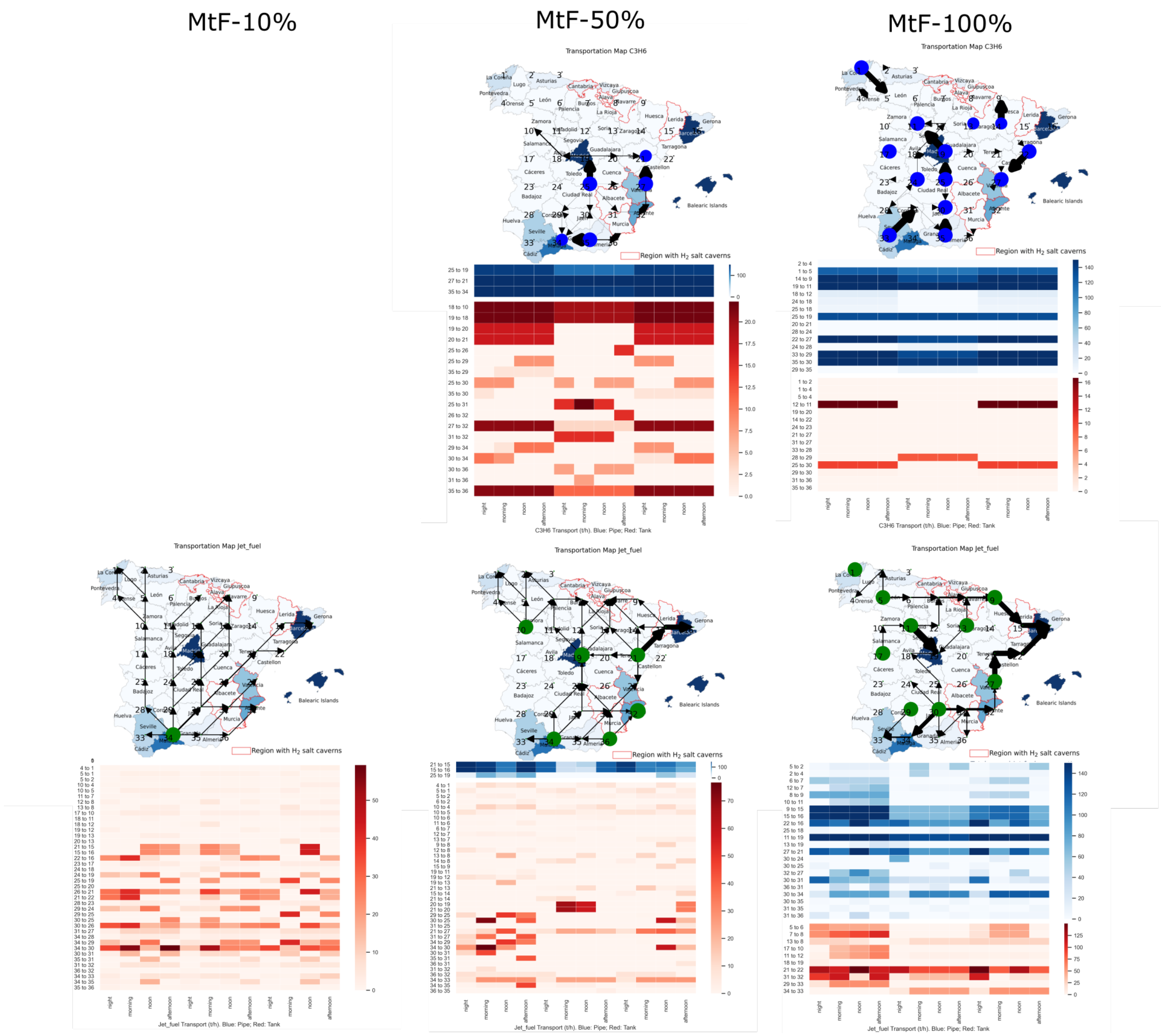


Figure E.5: Network performance at different levels of supply of jet fuel demand for the MtF route (cont.).

F Energy import scenarios

F.1 Fischer-Tropsch

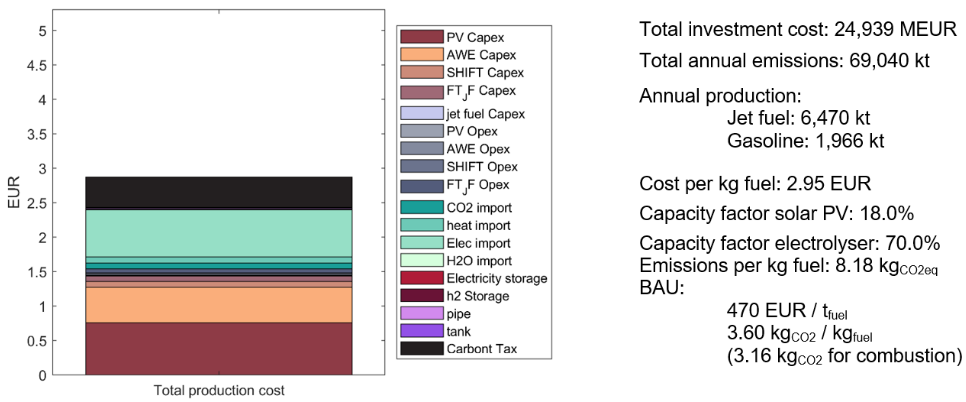


Figure F.1: Annual investment breakdown to produce jet fuel via Fischer-Tropsch including carbon tax and allowing electricity import from the grid and heat from natural gas.

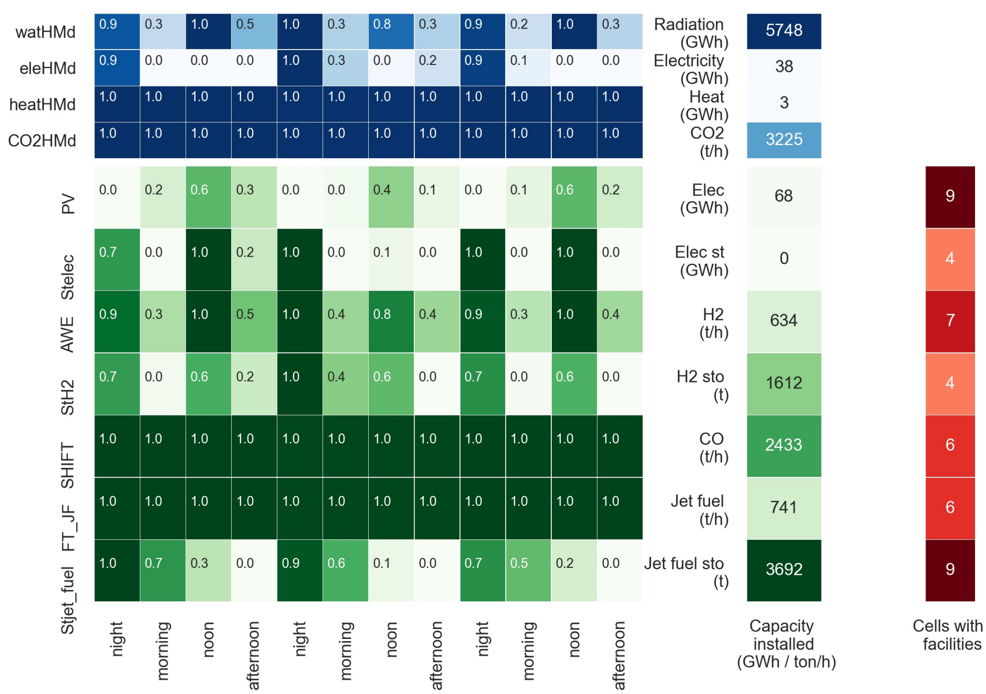


Figure F.2: Annual network performance to produce jet fuel via Fischer-Tropsch with import of electricity from the grid, heat from natural gas, and a carbon tax.

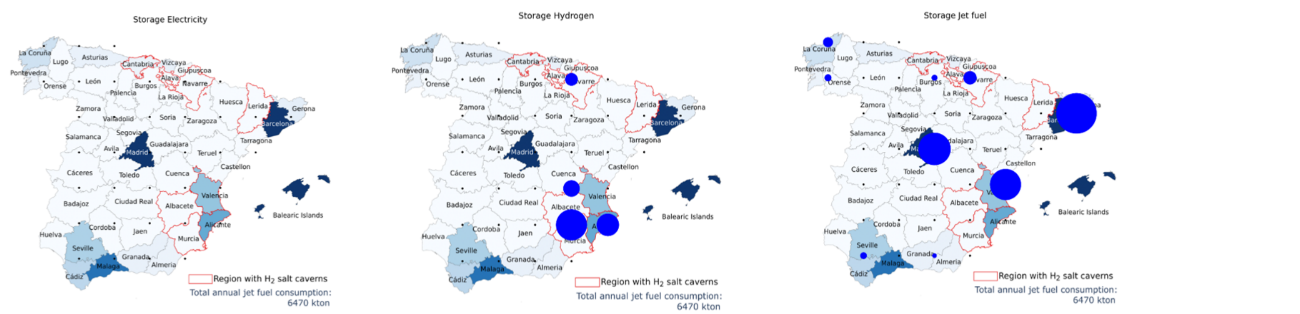


Figure F.3: Location of storage facilities in the FT route allowing external electricity and heat.

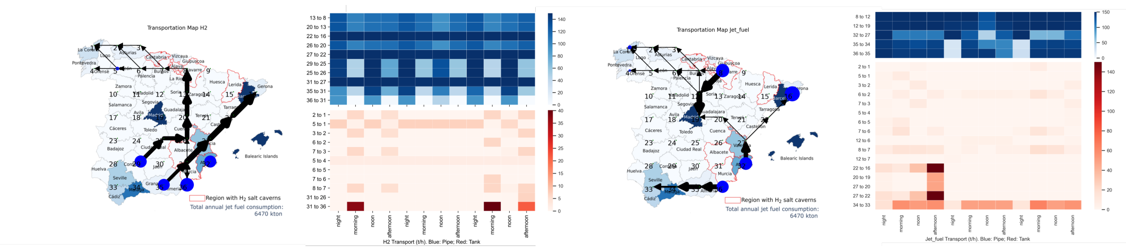


Figure F.4: Transportation map of resources in the FT route allowing external heat and electricity. Blue: Pipe transport; Red: Truck transport.

F.2 Methanol to fuels

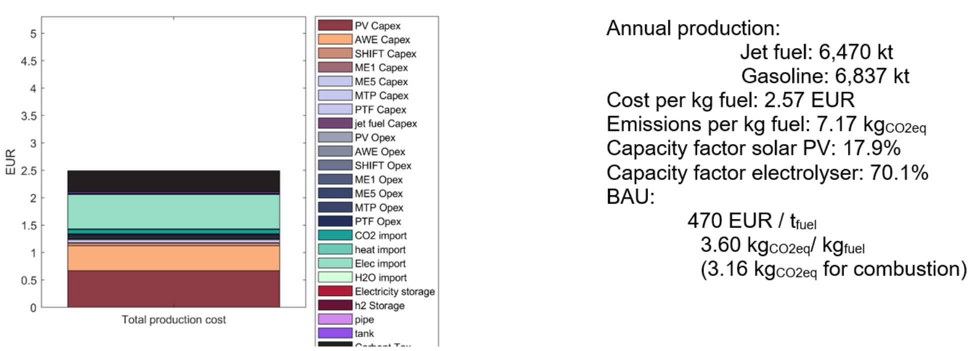


Figure F.5: Annual investment breakdown to produce jet fuel via MtF including carbon tax and allowing electricity import from the grid and heat from natural gas.

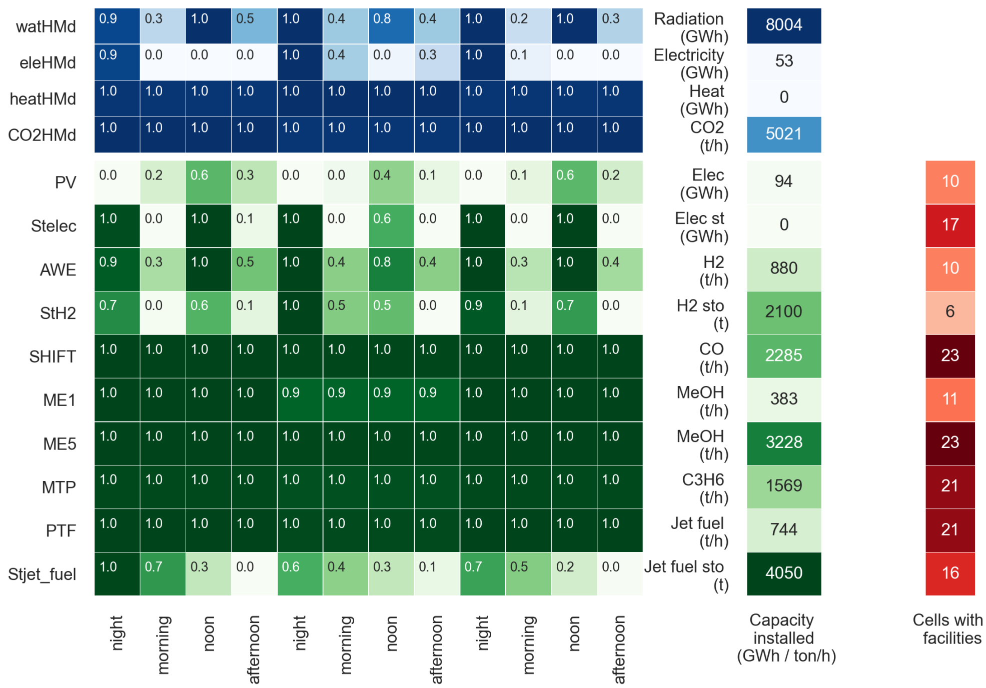


Figure F.6: Annual network performance to produce jet fuel via MtF with import of electricity from the grid, heat from natural gas, and a carbon tax.

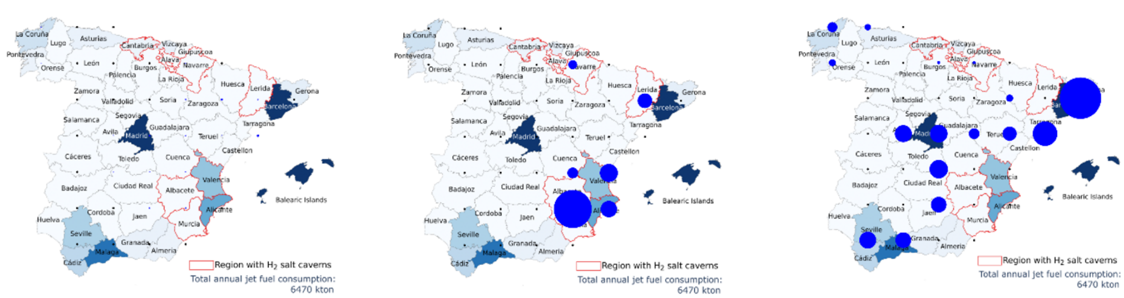


Figure F.7: Location of storage facilities in the MtF route allowing external electricity and heat.

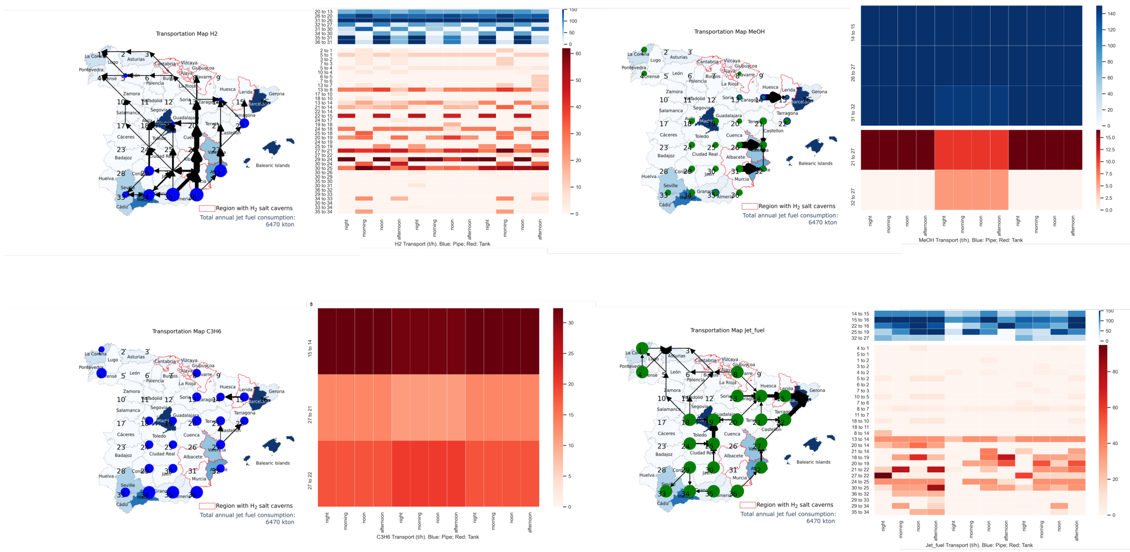


Figure F.8: Transportation map of resources in the MtF route allowing external heat and electricity. Blue: Pipe transport; Red: Truck transport.

F.3 Importing energy constraining emissions

Electricity is assumed to have a cost of 80 €/MWh during the day and 30 €/MWh during the night, releasing 360 kg_{CO2eq}/MWh. However, the cost of electricity and its emissions are expected to vary in the coming decades as the electricity mix decarbonises. According to the EU reference scenario 2016[6], emissions from the energy sector are expected to decrease from 80 to 95% by 2050. In order to analyse the potential integration of the network with the electricity grid, we now modify the cost and CO_2 emissions of the electricity being imported according to Table 3[7,8]. The cost reported is assumed to be the 'day' cost while the 'night' cost is reduced by 63%, as in the previous scenarios. Here, we also consider the technological improvements in PV and AWE. As reported in the Jet Fuel Network section, the import of electricity results in fuels with a higher lifecycle carbon footprint than those obtained from oil refineries. Given that the main objective of the RTN model is to generate low-emissions fuels, in this sensitivity analysis we constrain the CO_2 emissions of the liquid fuel to be equal or lower to those of the oil-based scenario (3.60 kg_{CO2eq}/kg_{fuel}). Therefore, the main objective of the analysis is to identify the maximum amount of electricity that can be imported from the grid without resulting in a fuel with worst carbon footprint. The RTN model is optimised in terms of the total cost including a carbon tax of 54 €/t_{CO2}. Heat import from natural gas is also allowed.

Table 3: Capital costs forecast for electricity, PV, CSP and AWE

Year	2015	2020	2030	2050
PV cost (€/kWh)	1300	810	684	360
PV emissions (kg_{CO2eq}/kWh)	67.8	62	44	8
CSP cost (€/kWh)	7027	5765	3915	2882
CSP emissions (kg_{CO2eq}/kWh)	46.7	42.7	36.8	25.0
Elec cost (€/MWh)	80	100	100	100
Elec emissions (kg_{CO2eq}/kWh)	0.42	0.36	0.17	0.05
AWE cost (€/kWh)	1200	1000	750	500

Fig. F.9 shows the results for the production of jet fuel according to the cases presented in Table 3. Fig. F.9 a)-b), we present the production cost and emissions per kg of fuel along with the amount of electricity being imported from the grid. In Fig. F.9 c)-d), we show the installed capacities of PV, AWE, and storage of electricity and hydrogen. Both routes present again a similar behaviour. In the case of 2015, the production of 1 MWh of electricity via PV and accounting for electricity storage is 285 €/MWh, while that of electricity from the grid including the carbon tax is 102 € and 53 € for the day and night periods, respectively. In consequence, the model imports as much electricity as possible (4% in FT and 10% in MtF) until the limit of CO_2 emissions is reached. By 2020, the cost per MWh of electricity from the network has reached 86 €/MWh, while that of electricity is now 120 and 57 €/MWh for the day and night periods. Since the electricity mix is still cheaper than the system PV-Storage, and its emissions are lower, a larger amount of electricity is imported (6% in FT and 15% in MtF). By 2030, electricity from the grid is still cheaper, allowing a further import as its emissions are expected to continue decreasing. The FT process shows an import of 28% reaching the 3.6

kg_{CO2eq}/kg_{fuel} and a cost of 2.85 €/kg_{fuel}. In the MtF process, 53% of electricity is imported releasing 1.6 kg_{CO2eq}/kg_{fuel} at a cost of 1.71 €/kg_{fuel}. Both routes show a reduction of installed capacities of PV, AWE around 20% while storage reduces by approximately 75%. Finally, by 2050, the technological improvements of PV and AWE allow for a further reduction in costs and CO_2 emissions while a maximum level of electricity import. In this scenario, the FT process reaches productions costs of 1.9 €/kg_{fuel} and emissions of 2.14 kg_{CO2eq}/kg_{fuel} while the MtF process reaches 1.7 €/kg_{fuel} and 1.59 kg_{CO2eq}/kg_{fuel}.

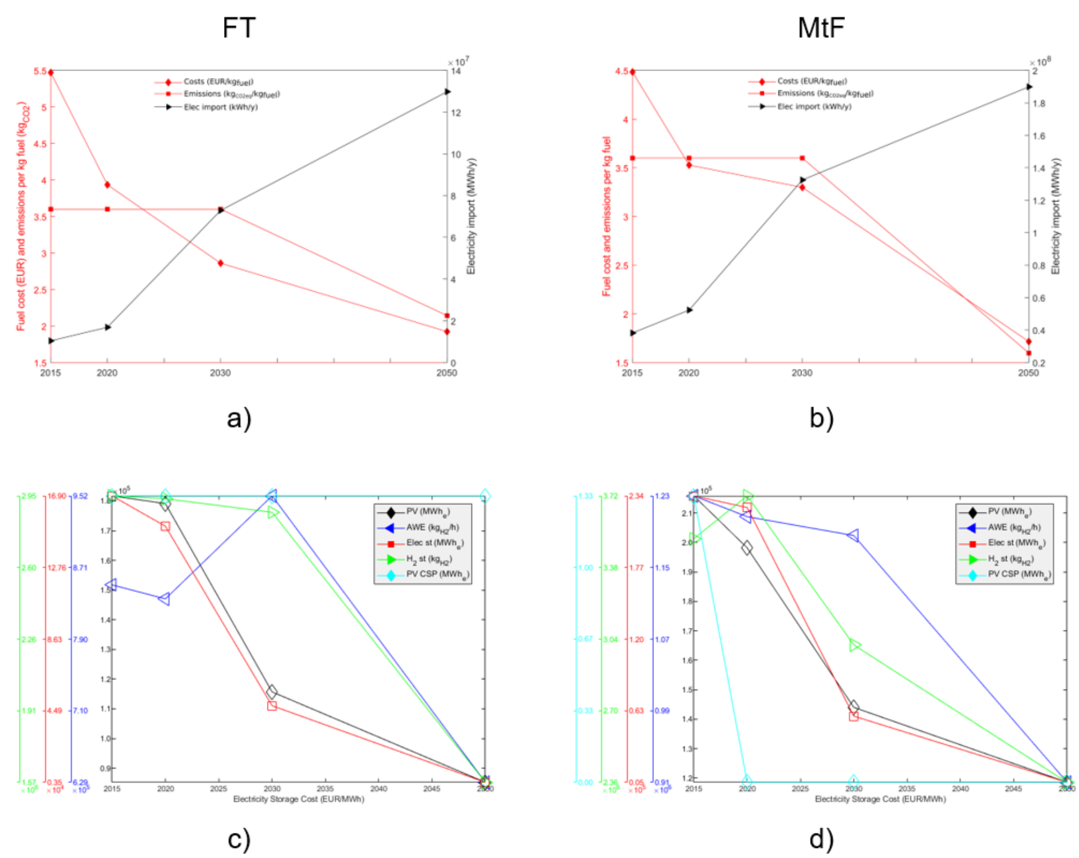
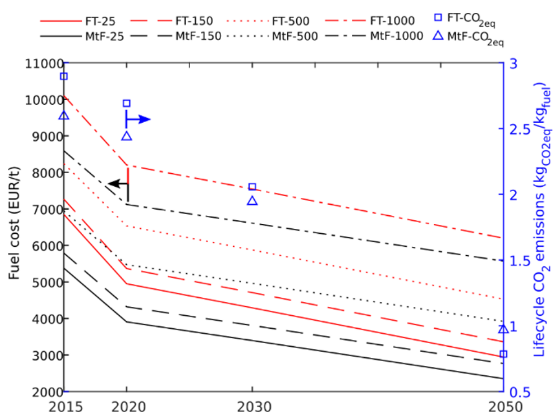


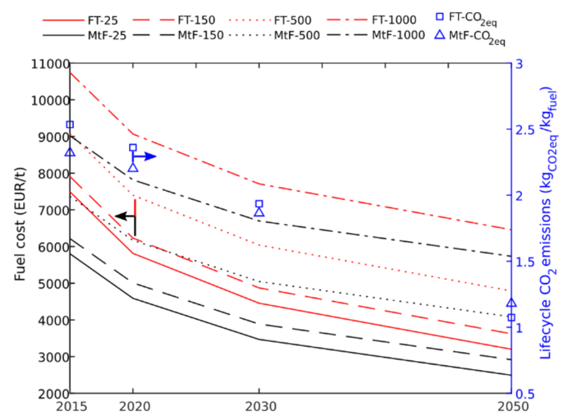
Figure F.9: Results for the sensitivity analysis over electricity price and CO_2 emissions for the production of jet fuel. a-b): total cost per ton of fuel (left axis) and electricity import allowed to maintain a maximum of 3.60 kg_{CO2eq}/kg_{fuel} (right axis). c-d): change in installed capacity of technologies in the network.

G Sensitivity analysis

G.1 Future costs of Solar electricity (PV and CSP) and AWE



(a) Fuel cost and emissions according to forecast performance of PV and AWE.



(b) Fuel cost and emissions according to forecast performance of CSP and AWE.

Figure G.1: Fuel cost and emissions according to forecast performance of PV, CSP and AWE.

G.2 Varying minimum operating load of AWE

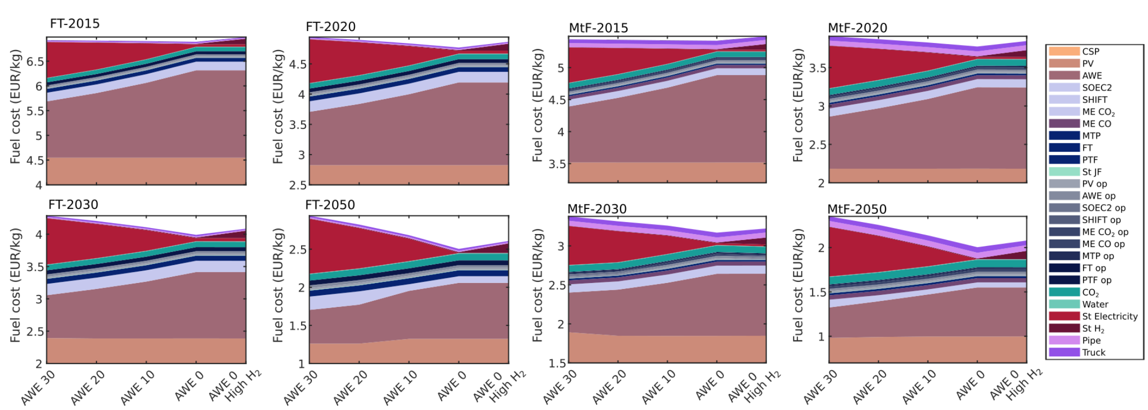


Figure G.2: Cost breakdown for the production of jet fuel at different minimum loads of AWE over time. Minimum AWE operating load: AWE 30: 30%, AWE 20: 20%, AWE 10: 10%, AWE 0: 0%, AWE 0 High H_2: 0% and H_2 storage cost of 1200 €/kg_{H2}.

H Sustainable aviation fuels

H.1 Beyond solar Efuels

Table 4: Parameters used to calculate the cost and emissions of Sustainable Aviation Fuels

Concept	2020	2050
Electrolyser (€/kW)	500-1200	400-1000
Electricity consumption (kWh/kg$_{H2}$)		50-85
Electricity cost		
Solar PV (€/MWh)	60-200	10-50
Wind (/euro/MWh)	45-120	20-70
Capacity factor Solar PV		0.2
Capacity factor Wind		0.5
Electricity CO_2 emissions		
Solar PV (kg$_{CO2eq}$/MWh)	40-75	5-20
Wind (kg$_{CO2eq}$/MWh)	8-20	4-8
Conventional jet fuel cost		0.43-0.75
2014 - 2019 (€/kg)	0.8	
BECCS costs of CO_2 avoided are reported in the range 15-250 €/t$_{CO2}$		

H.2 Air flight ticket concepts

According to Airlines for America,[9] 'The vast majority of the Cost Index is derived from quarterly financial and operational information collected by DOT (principally Form 41 reports), and historical data may be restated as warranted. Neither the Cost Index nor its components are seasonally adjusted because 1) users may find seasonal fluctuations of great interest and 2) leaving the data unfettered allows users to impose adjustments of their own choosing. Consequently, quarter-to-quarter movements in certain indices may be driven in part by the seasonality of the variables used to compute them'.

Labour. Wages, employee benefits (e.g., annuity payments, educational, medical, recreational and retirement programs) and payroll taxes (e.g., FICA, state and federal unemployment insurance). General management, flight personnel, maintenance labour, and aircraft and traffic handling personnel are all included in the calculation of labour costs.

Table 5: Airlines for America U.S. Passenger Airline Cost Index (PACI): 4Q 2019.

Concept	% OpEx
Fuel	17.7
Labour	32.9
Aircraft rent and ownership	6.7
non-aircraft rent and ownership	4.5
Professional services	8.6
Food and beverage	1.8
Landing fees	1.9
Maintenance material	1.4
Aircraft insurance	0.1
non-aircraft insurance	0.2
Passenger commission	0.8
Communication	0.8
Advertising and promotion	0.7
Utilities and office supplies	0.7
Transport related	12.8
Employee business	2.0
Other	6.5
TOTAL	100
Airport taxes	+20%
Profit	+15%

Fuel. Cost of aviation fuel used in flight operations, excluding taxes, transportation, storage and into-plane expenses.

Aircraft Rents and Ownership. The cost of aircraft rentals, depreciation and amortization of flight equipment, including airframes and parts, aircraft engine and parts, capital leases and other flight equipment. Non-Aircraft Rents Ownership. Principally, the total cost of airport terminal rents. Non-aircraft rents and ownership also includes the cost of hangars, ground service/support equipment (GSE), storage and distribution equipment, and communication and meteorological equipment.

Professional Services. The cost of legal fees and expenses (e.g., attorney fees, retainer fees, witness expenses, legal forms, litigation costs), professional and technical fees and expenses (e.g., engineering and appraisal fees, consultants, market and traffic surveys, laboratory costs), as well as general services purchased outside (e.g., aircraft and general interchange service charges).

Food and Beverage. The cost of purchasing beverages and food, commissary supplies and outside catering charges. Landing Fees. The cost of fees paid by the airlines to airports for runway and airport maintenance.

Maintenance Material. The cost of maintaining and purchasing materials for airframes, aircraft engines, ground property and equipment (excluding labor costs). Also includes the costs of maintaining a shop and servicing supplies (e.g., automotive, electrical, plumbing, sheet metal, small tools, glass and glass products, cleaning compounds).

Aircraft Insurance. The cost of flight equipment insurance, sometimes referred to as hull insurance. Non-Aircraft Insurance. The cost of insurance unrelated to the hull itself. This category is broken down by two categories: general insurance (i.e., buildings and contents, materials and supplies, third party liability, passenger baggage and personal property) and traffic liability insurance (i.e., passenger baggage and personal property, cargo liability and provisions for self-insurance).

Passenger Commissions. The costs paid to passenger travel agencies for services.

Communication. The total cost of equipment and intercommunication rental and installation charges, telephone and teletype equipment, telegraph and cable message charges and navigation facility charges.

Advertising and Promotion. Includes the cost of producing tariffs, schedules, timetables and other promotional and publicity expenses (e.g., television, radio, entertainment, photography, graphics).

Utilities and Office Supplies. The cost of light, heat, power and water, stationary, printing (e.g., labels, small signs, ticket stock, paper products, company manuals), shipping and mailing supplies and other office supplies as well as cleaning compounds, safety, electrical, engineering, drafting, blue prints and photographic supplies.

Transport-Related Expenses. As defined by DOT, transport-related expenses are expenses incurred for providing air transportation facilities associated with the performance of service which emanate from and are incidental to air transportation services performed by the carrier.

Employee Business Expenses. Includes expenses incurred for travel, lodging, meals, entertainment, membership fees/dues in professional or social clubs and associations. These expenses are incurred by officers, executives, directors, and other personnel.

Other Operating Expenses. Includes the cost of miscellaneous expenses such as outside flight equipment, excess of losses over insurance recoveries, interrupted trips expense, corporate and fiscal expenses, uncollectible accounts, clearance customs and duties.

Interest. The total interest paid on long term debt, capital and other interest expenses. Included in this worksheet is the cost associated with average book debt outstanding and estimated off-balance sheet debt.

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