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Global Potentials and Costs of Synfuels via Fischer–Tropsch Process

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Abstract: This paper presents the potentials and costs of synthetic fuels (synfuels) produced by renewable energy via PEM water electrolysis and the subsequent Fischer–Tropsch process for the years 2020, 2030, 2040, and 2050 in selected countries across the globe. The renewable energy potential was determined by the open-source tool pyGRETA and includes photovoltaic, onshore wind, and biomass. Carbon dioxide is obtained from biomass and the atmosphere by direct air capture. The potentials and costs were determined by aggregating minimal cost energy systems for each location on a state level. Each linear energy system was modelled and optimised by the optimisation framework urbs. The analysis focused on decentralised and off-grid synthetic fuels' production. The transportation costs were roughly estimated based on the distance to the nearest maritime port for export. The distribution infrastructure was not considered since the already-existing infrastructure for fossil fuels can be easily adopted. The results showed that large amounts of synthetic fuels are available for EUR 110/MWh (USD 203/bbl) mainly in Africa, Central and South America, as well as Australia for 2050. This corresponds to a cost reduction of more than half compared to EUR 250/MWh (USD 461/bbl) in 2020. The synfuels' potentials follow the photovoltaic potentials because of the corresponding low levelised cost of electricity. Batteries are in particular used for photovoltaic-dominant locations, and transportation costs are low compared to production costs.

Keywords: potentials; costs; synthetic; green; fuels; synfuels; global; Fischer–Tropsch

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1. Introduction

A net-zero emissions target by 2050 requires an enormous expansion of renewable energy systems. The International Energy Agency (IEA) suggests a four-times increase in photovoltaic and wind capacities in the next decade to reach this target in its recent roadmap [1]. Often, it is impossible to install such huge plants next to demand centres, which drives the need for energy carriers for dispatching and better integrating the intermittent renewable energy system. Synthetic fuels, also known as synfuels, are one such solution if produced from renewable electricity and carbon sources. Hydrogen has been considered a game-changer by many when it comes to the global exchange of renewable energy. Hence, several efforts have been put into green hydrogen technologies, such as PEM water electrolysis for high efficiency [2]. This trend towards green hydrogen also includes synfuels. Among these energy carriers, green hydrogen is often perceived as a more centralised solution, especially liquid hydrogen, which requires large-scale liquefaction units to become economically viable [3]. Often, this comes along with large hydrogen pipelines, which represent in most cases the least expensive onshore transport option [4]. Since some of the other alternative fuels can be directly produced in liquid form, a small-scale decentralised production plan can be implemented. These fuels can be easily transported using the existing infrastructure such as trucks and trains inland if needed. Another difficulty with hydrogen is the need to change the existing infrastructure on the demand side. Such difficulty can be avoided by utilising synthetic fuels, at least during the immediate future, as nearly no further infrastructure investments are needed [5]. The research on carbon-based synfuels was initially performed by producing methanol using nuclear power in the late 1970s [6]. Extracting carbon dioxide from the atmosphere for the generation of alternative fuels was also introduced in this period [7]. Initially, these solutions were seen as a way to store excess energy from nuclear power plants. With the decrease in the costs of intermittent renewable energy technologies such as solar and wind in recent decades, the focus has been shifted to view synfuels as energy carriers, and techno-economic assessments of such systems started appearing in the academic and industrial literature.

Recently, Brynolf et al. and Shemme et al. summarised most of the existing literature and investigated the costs of the production of various electro fuels such as methane, methanol, dimethyl ether, Fischer–Tropsch liquids, and gasoline [8,9]. These estimations range from EUR 10–3500/MWh. When Brynolf et al. performed their calculations based on the reference scenario data from these studies, they concluded that the cost range would be EUR 200–280/MWh in 2015 and EUR 160–210/MWh in 2030. Based on the data from Brynolf et al., Christensen et al. projected the theoretical maximum potential and costs of CO_2-based synthetic fuel production for EU Member States [10] and concluded that the potential volumes were limited and would only contribute to 0.15% of the total EU road transport fuel demand in 2030, even with very strong policy support. Another conclusion was that 45–50% of the total costs would come from the purchase of electricity. As the average full load hours of generation from PV and wind inside Germany are very low compared to other regions in the world, Agora Energiewende investigated the cost of the production of synthetic methane and liquid fuels imported from North Africa, the Middle East, Iceland (geothermal and hydropower), and the North and Baltic Seas (offshore wind) [11]. The total cost of liquid synthetic fuel from PV in North Africa was estimated at USD 0.19/kWh in 2020, USD 0.15/kWh in 2030, and as low as USD 0.11/kWh by 2050. The electricity generation costs are the main drivers in all cases, and the transport costs play a secondary role for synthetic liquid fuels. Although most of these studies presented the costs of production for synfuels, they assumed a certain price for renewable electricity in their analysis. The cost of production of renewable electricity varies significantly from location to location, which will be shown in Section 3.1. This implies that not all potential in a given region can be realised at the same price. In addition, as low-cost renewable energy technologies such as solar and wind are intermittent in nature, the whole system must be optimised for its generation at a higher temporal resolution. The interactions between different production plants of the systems (solar park, electrolyzer, and synfuel synthesis plant) and the corresponding storage elements (batteries, hydrogen tanks, carbon tanks, and synfuel storage) should be considered. For this reason, using an energy model is an ideal solution.

Considering the current political situation, depending on only one energy exporter seems to be risky for any country. The potential of synfuel production (or any other energy carrier) in a location is directly proportional to the potential of renewable electricity in that location. An overview of where such potential exists and where it costs less in the global picture seems to be resourceful. As part of the project ETSAP-Deutschland (IEA-ETSAP-TCP), the potential of liquid synthetic fuel is determined for selected countries with favourable renewable wind or solar conditions within each of the 16 TIAM regions [12]. This in turn helps with the extension and improvement of its database. The main purpose of this paper was to present the methodology and results of this work. The analysis focused on decentralised and off-grid synthetic fuel production. This paper is organised as follows:

Section 2 describes the different methods and tools used. Section 3 presents the results of this work. Section 4 discusses and summarises the results.

2. Methods

2.1. Energy System Modelling

The system boundaries of the energy model to analyse the production of synthetic fuel via electrolysis and the Fischer–Tropsch process are shown in Figure 1. This energy model consists of basically three parts: First is the renewable electricity generation by photovoltaic, onshore wind, and biomass (green). Second is the production of hydrogen including seawater desalination and intermediate hydrogen storage (blue). Third is the conversion of hydrogen to synthetic fuels by including carbon dioxide in the Fischer–Tropsch process (yellow). The energy system was considered to be decentralised and off-grid. There are no interaction and competition with local supply and demand.

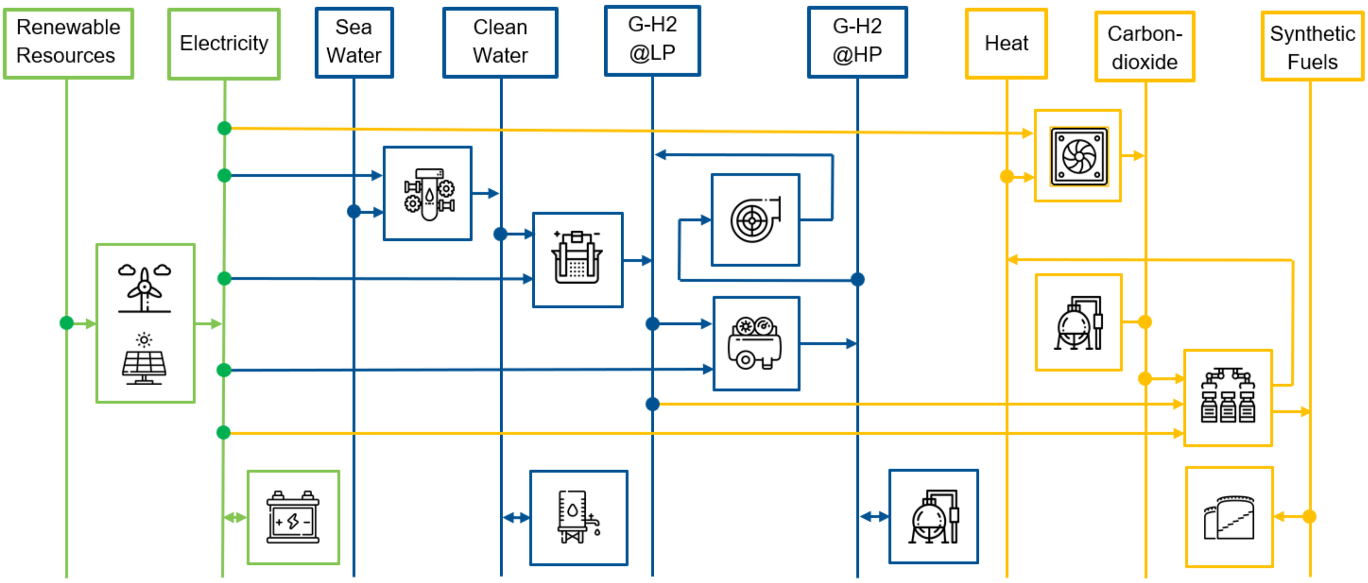

Figure 1. Reference Energy System (RES) (icons by flaticon.com (accessed on 30 January 2023)).

The first and second parts of the model correspond to green hydrogen production. The hydrogen produced by electrolysis can be stored at different pressure levels to balance and buffer the subsequent synthetic fuel conversion. The fluctuating renewable electricity can be stored in batteries as well to balance and increase the utilisation of the processes. It is also possible to store the clean water, as well as the synfuels in tanks. Synthetic fuels can be produced in various ways and various forms. The synfuel considered in this study is a mix of 62% diesel and 38% kerosene as a result of the Fischer–Tropsch synthesis of green hydrogen and carbon [13]. The carbon dioxide for the Fischer–Tropsch process is obtained from biomass and the atmosphere by direct air capture and can also be stored. The Fischer–Tropsch process produces slightly more waste heat than is needed for the direct air capture process. Finally, the produced synfuel will be transported by road to the nearest harbour for export.

2.2. Toolchain

Figure 2 shows how different open-source tools and all input parameters are connected. First, a region of interest is defined to set the scope of the analysis. Based on the scope of the analysis, the renewable potential of photovoltaic, onshore wind, and biomass was determined by an open-source tool, pyGRETA [14]. Then, the results of pyGRETA as potentials and representative time series of renewable energy generation served as the input for the energy system optimisation performed by urbs [15]. Finally, the minimal costs from the optimisation were combined with the costs of transport to the nearest harbour for export.

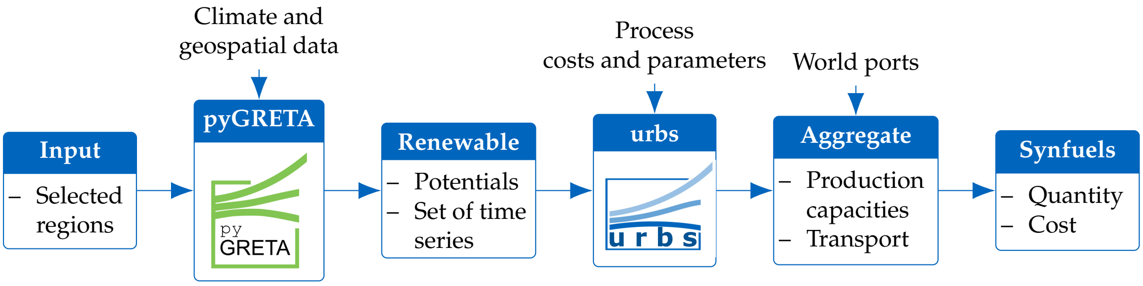

Figure 2. Toolchain.

For the global analysis, the selected countries were individually optimised on either the *GID-1* or *GID-2* level according to the *GADM* administrative areas [16] for three different demands of yearly quantities of synthetic fuels each. The decision to use either *GID-1* or *GID-2* was made qualitatively based on how big the corresponding regions are.

The optimisation for different yearly quantities within one region considered that the production costs depend on the quantities demanded. The three different quantities demanded are defined as the ratio of the total available renewable potential of the corresponding region since the maximum production quantity is limited by the renewable potential. The three synthetic fuel quantities demanded were set to 15%, 30%, and 45% of the total renewable potential considering process losses of about 50%. An hourly constant demand was considered in all cases. This process was repeated for every single GADM administrative area. Finally, all minimal cost energy systems were sorted by their production costs and aggregated either by region of interest or country to obtain the demand-dependent costs and potentials. For instance, in the TIAM region of Germany, for each of the 16 federal states, individual renewable potentials were generated, and an individual energy system was modelled and optimised for three different demands depending on the available renewable potential. All 16 $\times$ 3 minimal cost energy systems were then combined to obtain a supply curve and potential for the whole of Germany. The analogous procedure was performed for all of the TIAM regions, respectively.

2.3. Renewable Energy Potential

Renewable electricity generation is the first step in the process chain of synfuel production, as shown in Figure 1. The renewable technologies considered in this study were open-field PV, onshore wind, and biomass. These technologies are cost-effective, available in most parts of the world, and suitable for a decentralised approach when compared to other renewable technologies such as offshore wind and hydro. The analysis was carried out using the open-source tool *pyGRETA* [14]. It generates high-resolution potential maps and hourly generation time series for any user-defined region across the world for renewable technologies such as solar and onshore wind energy technologies. The spatial resolution of the tool is 250 m $\times$ 250 m at the Equator, which is further referred to as a pixel. The tool depends on historical weather data to calculate the hourly capacity factors and, in turn, the full load hours for PV and wind technologies. The hourly solar irradiance data [17], the hourly wind speed data [18] from the MERRA-2 reanalysis, and the average wind speed from the Global Wind Atlas [19] were used. The availability of each pixel was evaluated based on numerous customizable land use criteria, which were adopted from Ryberg et al. [20]. Within the land eligibility analysis, 38 different types of land areas with specific buffer distances for open-field PV and onshore wind turbines were excluded. Three different kinds of exclusion categories were considered: physical limits, sociopolitical constraints, and nature conservationareas. The physical limitations considered were the maximum slope (10° for PV and 17° for onshore wind turbines), coasts, rivers, wetlands, and salt flats based on data sources such as CCI [21]. Sociopolitical constraints were considered by applying minimum distances to settlements (200 m for PV and 1000 m for wind turbines), roads, railways, power lines, and airports. In addition, land use conflicts were avoided by excluding woodlands and possible croplands for PV usage based on data from Open Street Map [22]. Nature conservationareas excluded a different kind of already protected area from the World Database of Protected Areas [23], as well as protected areas for birds to avoid birds striking the wind turbines. Annual energy generation potentials and corresponding CO_2 equivalent emissions from biomass were also taken from pyGRETA, which depends on annual crop production, forest wood production, and livestock density data [24].

2.4. Optimisation

The energy model described in Section 2.1 and shown in Figure 1 was optimised so that, for the given input time series and demands, the supply costs of synthetic fuels were minimal. The modelling and optimisation of the energy system were performed with the linear optimisation tool *urbs* [15]. urbs is a linear programming optimisation model for capacity expansion planning and unit commitment for distributed energy systems. It was created by the Chair of Renewable and Sustainable Energy Systems at the Technical University of Munich and is open-source and can be applied on multiple scales from urban neighbourhoods to continents. The result of the optimisation in urbs is a minimal cost energy system that connects input and demand time series while considering all limitations and constraints such as process dependencies, capacity limitations, and technology costs. In this analysis, an individual urbs model was created for each considered year and region of interest based on the energy system in Figure 1, the renewable potential by pyGRETA in Table in Appendix A.2, and the technological input parameters in Table 1. These individual urbs models were then optimised independently so that a minimal cost energy system was achieved.

2.5. Scope and Assumptions

The scope of the analysis was for selected countries so that a well-balanced global coverage according to the world regions utilised in TIAM was achieved. The same selection of countries was applied in Franzmann et al. [25]. The analysis was conducted for the years 2020, 2030, 2040, and 2050. The technological parameters were mainly adopted from the *IEA G20 Hydrogen report* [26] and are shown in Table 1.

Table 1. Technology costs and parameters.

Technology	**CAPEX**				**OPEX of CAPEX (%)**	**Efficiency (-)**				**Lifetime (a)**	**Source**
	2020	**2030**	**2040**	**2050**		**2020**	**2030**	**2040**	**2050**		
PV (EUR/kW)	703	395	340	326	1.0	1.00	1.00	1.00	1.00	25	[27]
Wind (EUR/kW)	1 257	1 137	987	923	3.0	1.00	1.00	1.00	1.00	25	[27]
Biomass (EUR/kW)	2 037	1 954	1 892	1 826	3.5	1.00	1.00	1.00	1.00	25	[28,29]
PEM (EUR/kW)	1 023	795	653	511	1.5	0.64	0.69	0.72	0.74	19	[26]
DAC (EUR/(t a))	800	350	270	220	3.7	-	-	-	-	25	[13]
FT (EUR/kW)	1 011	864	864	642	4.0	0.73	0.73	0.73	0.73	25	[26]
Turbine (EUR/kW)	220	220	220	220	2.0	1.00	1.00	1.00	1.00	20	-
Compr. (EUR/kW)	1 100	1 100	1 100	1 100	2.0	0.87	0.87	0.87	0.87	20	[30,31]
Desalin. (EUR/(kg a))	43	43	43	43	2.0	-	-	-	-	20	[32,33]
Liquef. (EUR/kW)	1 332	1 332	1 332	1 3320	2.0	0.68	0.68	0.68	0.68	20	[34]
Battery (EUR/kWh)	277	147	124	102	2.5	0.95	0.95	0.95	0.95	15	[35]
LH2-Storage (EUR/kWh)	0.85	0.85	0.85	0.85	2.0	1.00	1.00	1.00	1.00	20	[26]

Weighted Average Cost of Capital (WACC) for all technologies of 8%.

3. Results

This section provides the results of our analysis as described in Section 2. The selected countries can be seen in Figure 3. Countries in grey were not considered. This section focuses on the two countries Germany and Australia due to their contrary renewable potentials. Australia has huge potentials for photovoltaic and comparable low wind potentials, whereas Germany has a balanced mix of both potentials. The full cost potential curves for the years can be found in Appendix A.1.

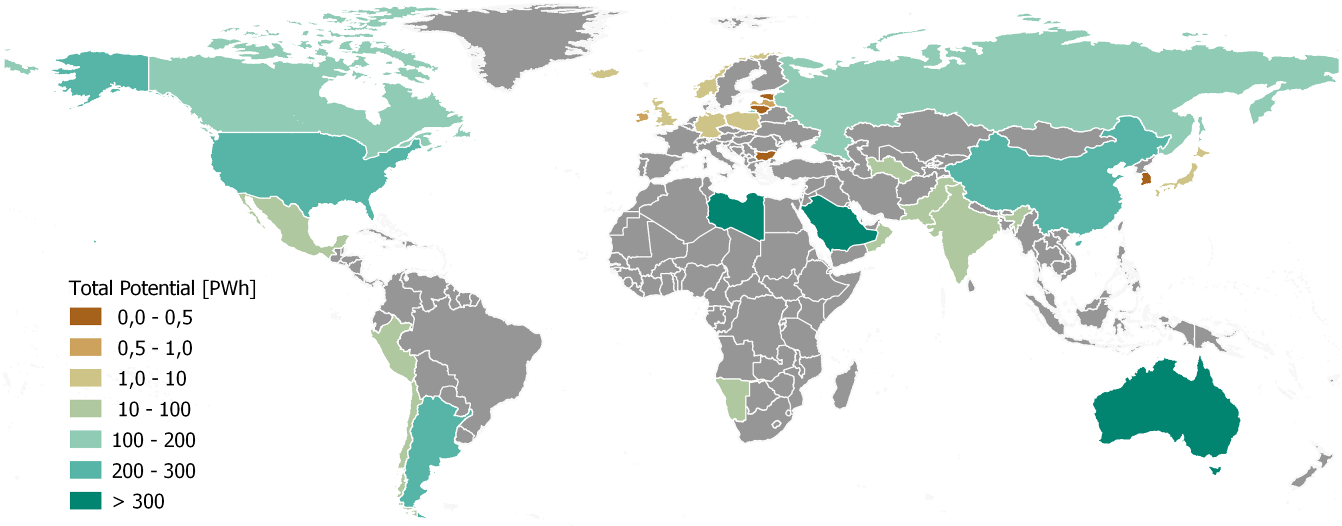

Figure 3. Renewable energy potential (open-field PV, onshore wind, biomass).

3.1. Global Renewable Potential

Figure 3 shows the renewable potential of photovoltaic, wind, and biomass. The assumptions and methodology are explained in Section 2.3. The remaining countries in grey were neglected due to computational limitations. The computational time for the previouscountries was about 170 h while using 70 cores. The total potential of the selected regions was 2875 PWh. There are huge potentials in North and South America, Africa, and Australia. Although Russia and Canada are big countries with many areas available, their energy potential is comparatively small due to long winters. This is different in the case of Libya and Saudi Arabia, where the comparatively small areas have higher potential due to the comparable very high full load hours of open-field PV. European countries in general have the least potential both due to smaller areas available and the lack of good solar irradiance throughout the year. The detailed power and energy potentials of each selected country can be found in Appendix A.2. The hourly generation profile varies from pixel to pixel due to factors such as land type, topography, and latitude position, as shown in Figure 4. On average, the full load hours in Argentina within a GID-1 region vary by 98% for onshore wind, whereas this variance is just about 19% for open-field PV. To effectively transfer the high-resolution pixelwise results from pyGRETA into an energy model with a much smaller spatial resolution such as states or provinces, the generation time series of three different representative locations were considered for wind energy, where each represents the best or least expensive as 20%, the middle as 40%, and the last 40% of the potential, respectively.

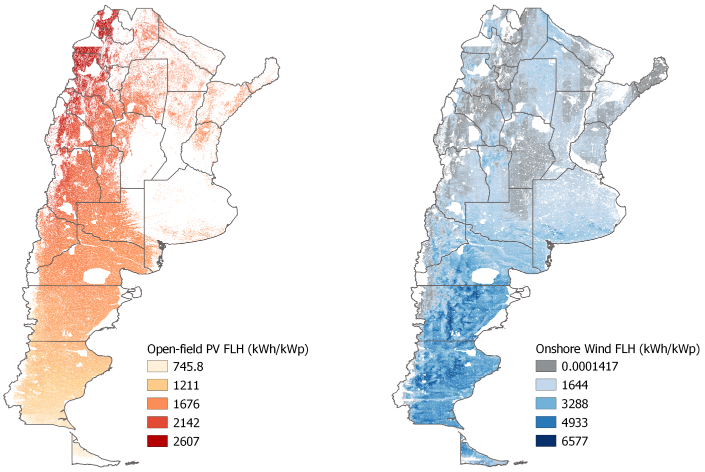

Figure 4. Exemplary full load hour maps of Argentina GID-1 level for open-field PV and onshore wind.

3.2. Supply Curves

The supply curves in Figure 5 show the export costs dependent on the amount of exported energy of synfuels in 2020 and 2050. Economically favourable countries such as Australia (ANZ), those in Africa (AFR), the Middle East (MEA), and Central and South America (CSA) have a flat curve and start low. Countries such as Germany (DEU), Japan (JPN), and South Korea (KOR) have less potential and, hence, are economically unfavourable for the production of synthetic fuels. In total, large amounts of synthetic fuels compared to the global primary energy consumption of about 180 PWh are available up to EUR 250/MWh in 2020 and EUR 110/MWh mainly in Africa, Central, and South America, as well as Australia in 2050. The export costs are more than halved from 2020 to 2050.

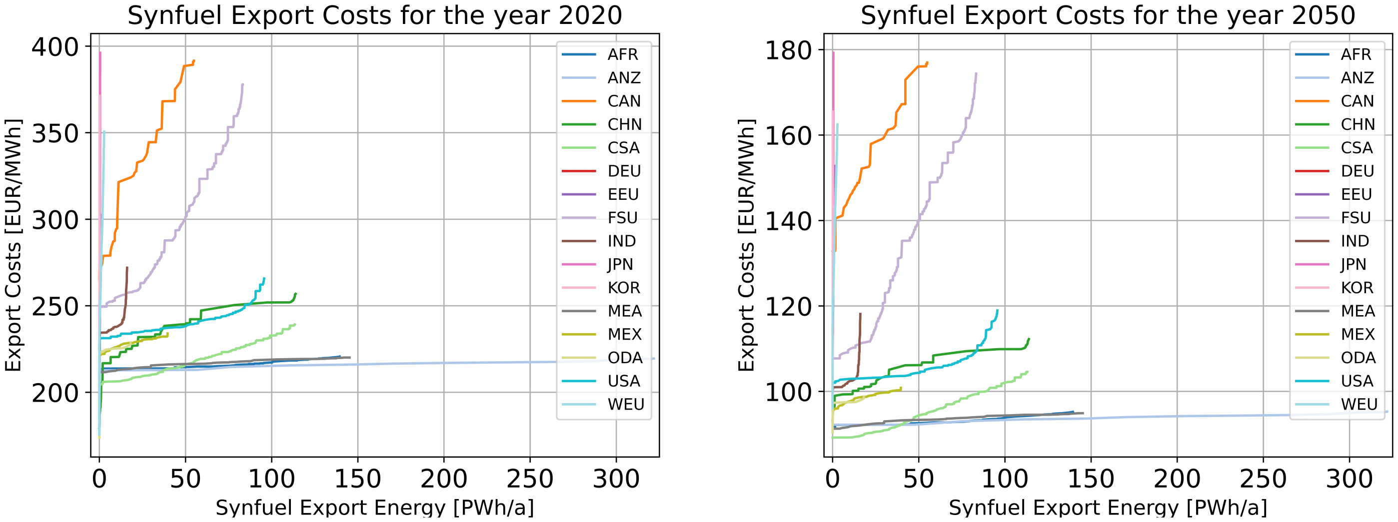

Figure 5. Supply curves for synthetic fuels in 2020 and 2050.

3.3. Energy Flow

The energy flows of synthetic fuel production for Germany and Australia in 2050 are shown in Figure 6. For both locations, the overall efficiency increases tremendously from 2020 to 2050 due to technology and process improvements, in particular for electrolysis, concerning efficiency and costs. The overall efficiency for Australia is 43% in 2020 and 49% in 2050, whereas for Germany, it is 45% in 2020 and 52% in 2050. Beneficial solar locations such as Australia use photovoltaics as the main energy source, whereas in Germany, for example, wind and photovoltaics are equally used. The biomass potential is comparable low to the photovoltaic potential in Australia with a share of about 0.01%, as can be seen in Appendix A.2. Carbon dioxide in this case is directly obtained from the atmosphere by direct air capture. The largest energy loss happens in PEM electrolysis, being about 22%. After that follows the Fischer–Tropsch process during the conversion from hydrogen to synfuels by about 14%, electricity curtailment by about 9%, and direct air capture by about 3%. Electricity curtailment describes the reduction in the output below what could have been produced by, for example, switching off wind turbines. The combination of photovoltaics and wind reduces the need for electricity curtailment. This effect is shown by comparing the curtailment of various countries where the mix of photovoltaics and wind differs. For instance, the electricity curtailment of Australia is 7% and of Germany is 10% because Australia uses only photovoltaics in contrast to Germany. Australia has almost about 50% more electricity curtailment than Germany. Desalination can be neglected in both cases.

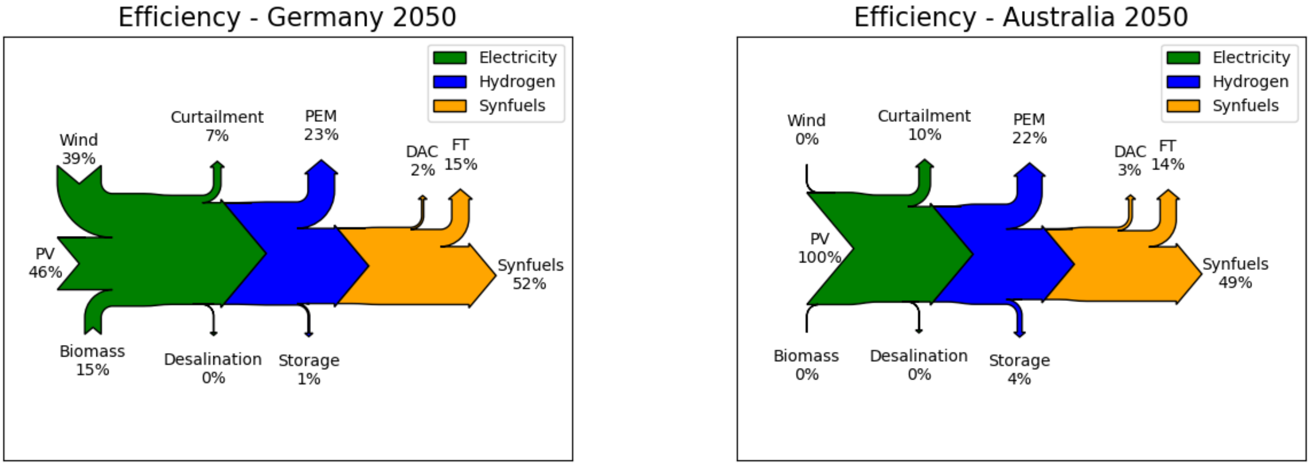

Figure 6. Energy flows for Germany and Australia in 2050.

3.4. Technology Utilisation

The full load hours of each technology for Germany and Australia in 2050 are shown in Figure 7. The full load hours in Australia are almost constant since mainly photovoltaics and wind energy only at the very end are used. In contrast to Australia, the full load hours in Germany decrease with the increasing amount of produced synthetic fuels. The utilisation rate of Direct Air Capture (DAC) is the highest of all processes for both Germany and Australia, but starts later in Germany because biomass is used as the carbon dioxide source first. The utilisation rate of the Fischer–Tropsch process is also quite high. The full load hours of PEM electrolysis are much higher in Germany at the beginning than in Australia because of the optimised photovoltaic and wind electricity mix. The full load hours of photovoltaics are almost constant, as expected, and of wind slightly decrease by the amount of synthetic fuel.

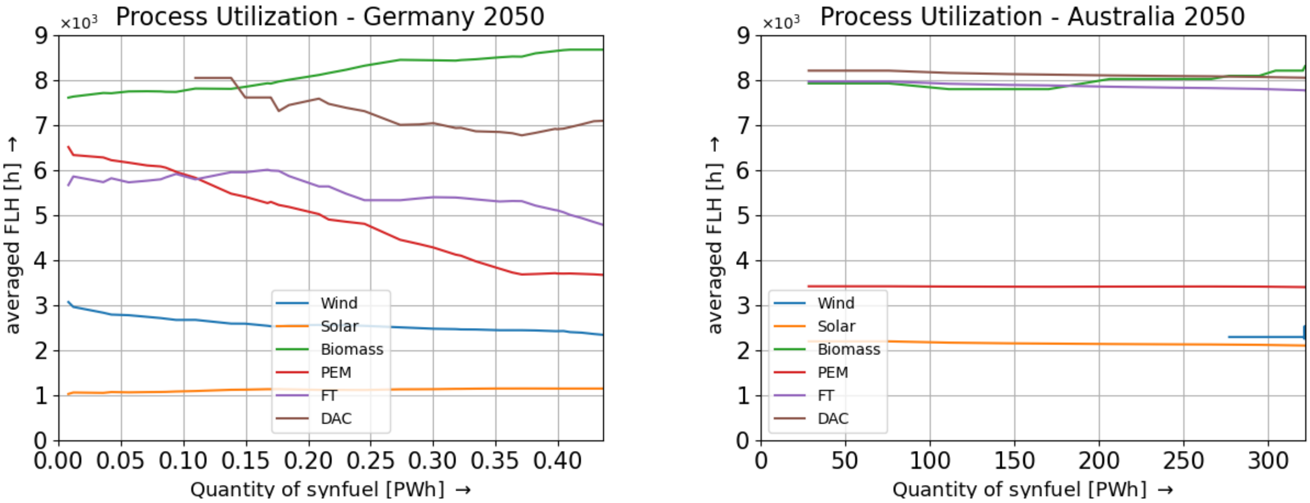

Figure 7. Utilisation of each technology for Germany and Australia in 2050.

The utilisation and, thus, export costs are, for locations with high solar potential, almost constant and independent of the exported amount of synthetic fuels. This is in line with the findings for green hydrogen exports in Franzmann et al. (Forschungszentrum Jülich). The reason for that is that the photovoltaic potential within a country is homogeneously distributed. Wind potentials within a country, on the contrary, are heterogeneously distributed and, therefore, vary in their full load hours. As a result, the best wind location with high full load hours and, thus, a low levelised cost of electricity was chosen first. The effect is that the full load hours are high at the beginning and decrease with the increasing amount of exported synthetic fuel. On the contrary, the countries where photovoltaics as an energy source dominates have a flat curve since the full load hours are homogeneously distributed. The H_2 storage is used to increase the utilisation of the Fischer–Tropsch process and direct air capture technology. The carbon dioxide comes from biomass first while producing electricity, and afterwards, it is obtained by direct air capture from the atmosphere.

3.5. Process Costs' Allocation and Development

The process costs' allocation and development for Germany and Australia from 2020 to 2050 are shown in Figure 8. In general, the main cost drivers are electricity generation, electrolysis, and conversion into hydrocarbons. The export costs can be reduced by approximately 50% until 2050 due to reduced process costs and optimised processes, which are caused by the underlying assumptions for the technologies. Furthermore, the analysis also shows that the cost of the transport of synthetic fuels is about 1–2%, which is very low compared to the cost of production, as also shown in [36]. In Germany, the average export cost starts at EUR 240/MWh in 2020 and decreases to EUR 130/MWh in 2050. CO_2 storage is used in combination with biomass because more CO_2 is emitted than electricity is used for the synfuel production. Batteries are hardly used except for photovoltaic-dominant locations such as Australia.

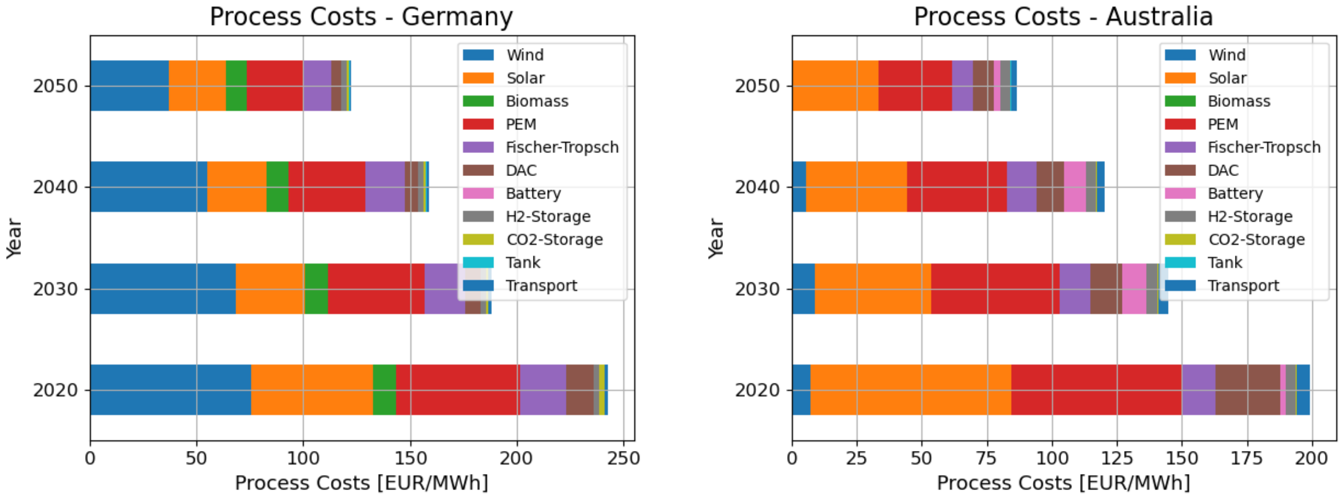

Figure 8. Process costs' development and allocation.

In Australia, the average export cost starts at EUR 180/MWh in 2020 and decreases to EUR 80/MWh in 2050. The energy generation in Australia only relies on photovoltaics and batteries in contrast to Germany because of its very low photovoltaic electricity generation costs.

4. Summary and Discussion

In this paper, the methodology and results of decentralised and off-grid green synthetic fuel production were presented. The resulting global potentials and costs give an insight into the possible future of synthetic fuels and serve as the input to the TIMES Integrated Assessment Model (TIAM) to analyse the role of synfuels in a full global energy system. The results above in Section 3 showed in general that there is tremendous potential for green synthetic fuels in the future. The export costs decline by about 50% until 2050. However, the export costs for larger quantities (USD ∅ 200/bbl) will still be high compared to the latest fossil fuel prices (USD ≈ 80/bbl). The main cost drivers are green energy generation (photovoltaic, wind, and biomass), followed by electrolysis, which is in line with Christensen et al. [10] and Agora Energiewende [11]. The greatest economic potential of synthetic fuels corresponds in principle to the photovoltaic potential, especially towards 2050, since the levelised cost of photovoltaics becomes the lowest.

Further comparison to the literature showed that the results of this study are in the range of previous studies. Brynolf et al. and Shemme et al. concluded that the cost range would be EUR 200–280 /MWh in 2015 and EUR 160–210/MWh in 2030 [8,13]. The novelty and contribution of this work to the literature are that the production of synthetic fuels was investigated on a global scale. This analysis showed how renewable energy potentials such as for photovoltaics, wind power, and biomass influence synthetic fuels' export costs. It was also shown that a mixture of photovoltaics and wind is favourable, except for countries with very good photovoltaic potential such as, for example, Australia. However, this study has some uncertainties and limitations. It is important to mention that the results presented were an outcome of decentralised and off-grid synthetic fuels' production for the sake of simplicity. Competition and interaction with local energy demand needs to be considered, especially since direct use of renewable electricity is often more efficient and is thus more economical. For this reason, the cost potential curves at low costs will have a different course if the best renewable potentials are used to fulfil other demands instead and are not available for the production of synthetic fuels. Moreover, there is uncertainty concerning the technological development and costs in the future. This analysis showed that the export costs greatly depend on the process costs. Thus, the final export costs depend strongly on the underlying assumptions. It needs to be mentioned that our established toolchain is quite flexible and can be easily applied to other optimised energy systems at multiple scales.

Based on a 1.5 °C scenario with the energy system model TIAM, the results [37,38] showed that synfuels will primarily be used in the transport sector in the future. The advantage of synfuels leads to a fuel switch, as existing technologies do not need to be replaced as synthetic fuels do not have a carbon footprint. Therefore, synfuels are an intermediate solution for certain existing technologies (e.g., aviation, shipping, and industrial technologies) before investing in new capacity. Even if the transport sector can mostly be fuelled by synfuels, there is still the competition of direct electricity use by electric vehicles. In the long run, synthetic fuels will be used in heavy duty transportation and a share in both domestic and international aviation, as the results showed. The demand for passenger transport is fully satisfied by electric vehicles, while shipping is fuelled by hydrogen. There is also the possibility to use synthetic fuels in other sectors (e.g., industry, residential, etc.) for heat generation, but as the results showed, it is more cost optimal to use electricity or gas combined with Carbon Capture and Storage (CCS). Compared to hydrogen, synfuels show a huge advantage in diversification. While hydrogen has its least expensive production region in the Middle East, synfuels' production does not differ that much according to the sun-rich regions. The reason for this behaviour is based on the feasible biomass potentials of each region as a source of carbon for the Fischer–Tropsch process. In addition, synfuels have the advantage that they can use existing infrastructure, so that new infrastructure does not have to be built, which is often a time-consuming process. Since there are still some regions that export oil and gas today, it is promising to see that they also have high potential for synfuel production. This would give these regions the chance to maintain their foreign trade and to supply other regions that have less access to these potentials. Regarding the security of supply, synfuels offer the advantage that there is good diversification, and they do not necessarily have to be politically forced.

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Abbreviations

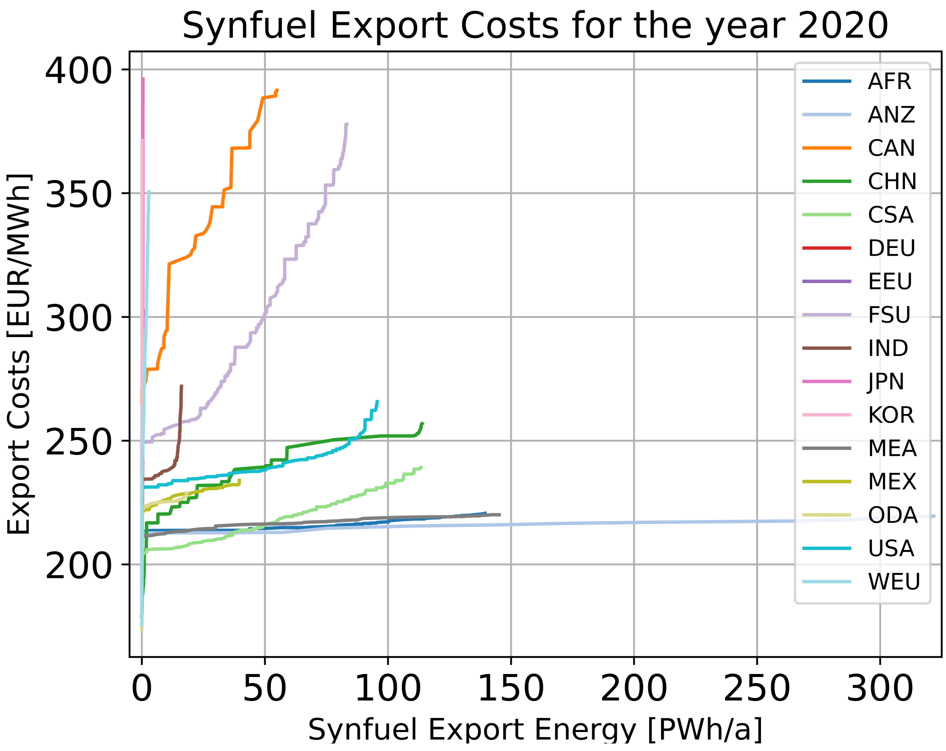
The following abbreviations are used in this manuscript:

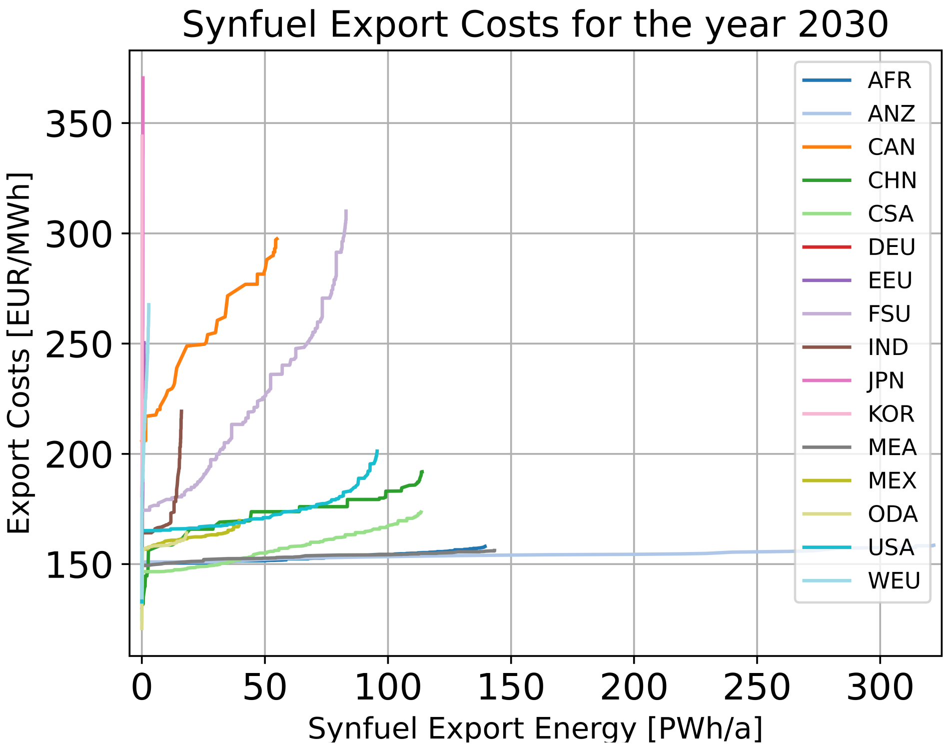
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
DAC	Direct Air Capture
FT	Fischer–Tropsch
IEA	International Energy Agency
HP	High Pressure
LP	Low Pressure
OPEX	Operational Expenditures
PEM	Polymer Electrolyte Membrane (electrolysis)
PV	Photovoltaics
pyGRETA	python Generator of REnewable Time series and mAps
TIAM	Times Integrated Assessment Model
TUM	Technical University of Munich
urbs	linear optimisation model for distributed energy systems

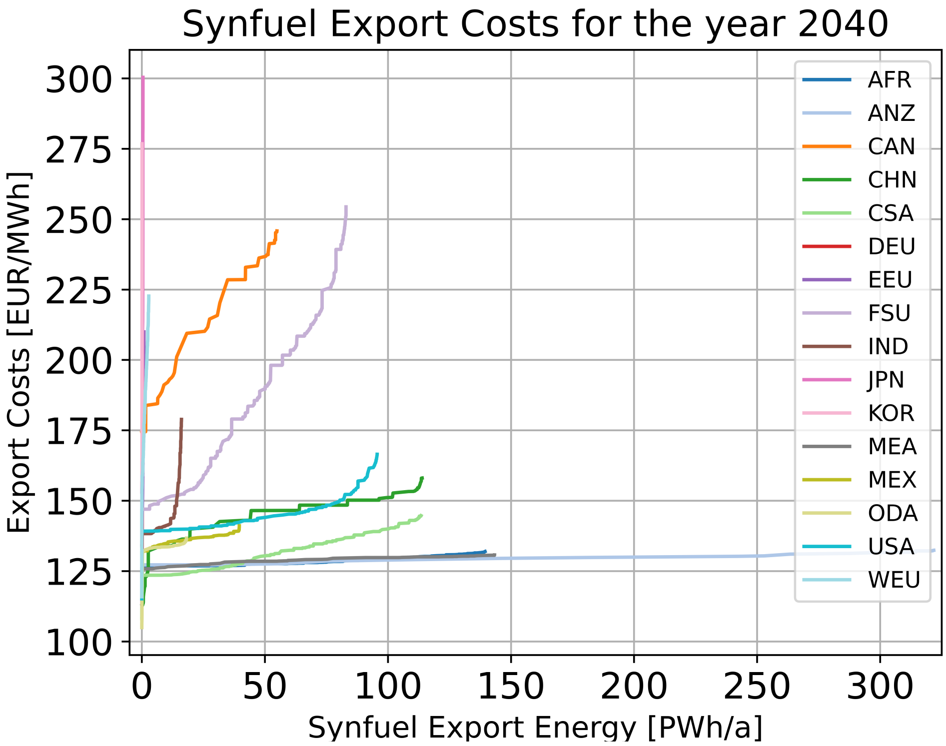
Appendix A

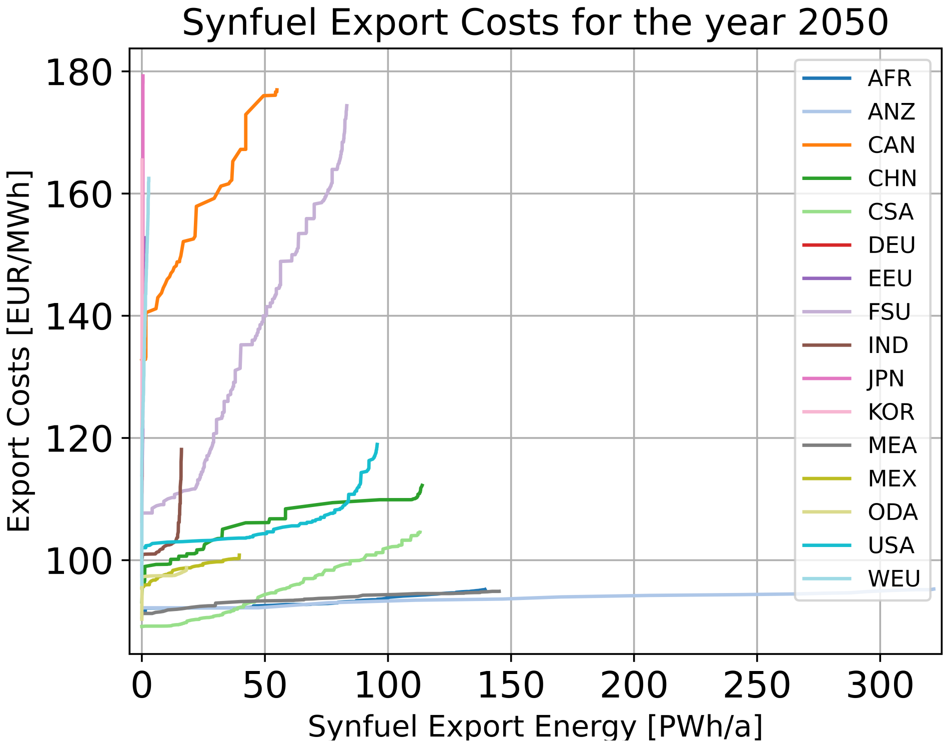
Appendix A.1

The following four figures show the full cost potential results from all years considered.




Synfuel Export Costs for the year 2030
Export Costs [EUR/MWh]
350
300
250
200
150
0
50
100
150
200
250
300
Synfuel Export Energy [PWh/a]
AFR
ANZ
CAN
CHN
CSA
DEU
EEU
FSU
IND
JPN
KOR
MEA
MEX
ODA
USA
WEU


Synfuel Export Costs for the year 2040
Export Costs [EUR/MWh]
300
275
250
225
200
175
150
125
100
0
50
100
150
200
250
300
Synfuel Export Energy [PWh/a]
AFR
ANZ
CAN
CHN
CSA
DEU
EEU
FSU
IND
JPN
KOR
MEA
MEX
ODA
USA
WEU



Appendix A.2

	Open-Field PV		**Onshore Wind**		**Biomass**	
Country	**Power (GW)**	**Energy (TWh)**	**Power (GW)**	**Energy (TWh)**	**Energy (TWh)**	**Emissions (Million Tons of CO_2 Eq.)**
Libya	139,492.2	292,928.7	10,447.6	15,407.1	1.7	0.6
Namibia	16,316.4	35,750.6	3222.3	4326.6	2.0	0.7
Australia	35,0320.8	734,414.7	36,612.9	67,927.4	87.2	44.1
Canada	109,452.9	96,253.7	39,656.4	46,159.1	185.7	72.9
China	137,741.6	240,150.8	40,990.2	45,890.5	1772.4	717.9
Argentina	102,489.7	177,895.8	14,387.2	26,840.9	192.9	79.5
Chile	22,494.2	48,753.5	2831.3	2477.0	23.5	8.5
Peru	12,192.4	27,279.8	5101.6	738.8	28.9	15.2
Germany	341.6	394.6	284.8	558.8	127.6	49.6
Bulgaria	137.6	215.4	276.7	192.3	26.1	10.1
Poland	259.1	315.4	412.8	860.8	62.9	24.6
Estonia	120.5	127.0	164.0	367.3	7.7	2.8
Lithuania	120.1	133.2	214.2	288.4	13.9	5.4
Latvia	183.2	195.8	255.6	442.7	9.6	3.7
RUS	88,953.9	73,842.7	82,489.3	80,540.8	272.2	107.4
Turkmenistan	29,444.2	50,251.3	2793.8	3752.8	3.6	1.5
India	17,410.8	31,611.9	11,124.2	8690.6	1349.7	646.5

Country	Open-Field PV		Onshore Wind		Biomass	
	Power (GW)	Energy (TWh)	Power (GW)	Energy (TWh)	Energy (TWh)	Emissions (Million Tons of CO_2 Eq.)
Japan	268.3	404.7	795.4	834.0	39.0	15.9
South Korea	50.9	81.7	184.0	192.9	15.0	6.0
Oman	24,995.3	52,113.9	1856.3	1995.8	0.1	0.0
Saudi Arabia	141,952.6	294,594.0	10,671.5	13,803.3	3.4	1.3
Mexico	47,235.8	93,199.4	8840.0	6096.1	150.4	75.1
Pakistan	21,365.4	42,249.9	3592.6	3032.5	165.4	84.2
USA	111,868.7	188,404.2	35,491.8	49,294.8	992.6	385.2
United Kingdom	604.6	606.3	330.7	850.1	1.8	0.7
Ireland	141.9	153.0	145.1	423.5	4.9	1.9
Iceland	1617.9	1286.8	353.8	904.5	0.0	0.0
Norway	2392.1	1917.8	965.5	944.0	4.3	1.6

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