Appendix

This appendix describes how we derived the figures and tables in the perspective. The R-scripts and data used to generate the figures can be found online at our Github repository at *https://github.com/INWE-BOKU/Perspective_Trade*. For external data sources, we aimed at allowing for a full automated download, as shown in R-script *scripts/00_reFUEL_Download.R*. Some data providers require a registration of users, therefore a full automatic download is not possible. A brief tutorial on how to download these data sets can be found in the download script.

Figure 1: trade in integrated assessment scenarios

Details of how figure 1 was generated can be found in the R-script *scripts/01_reFUEL_Figure1.R*.

Existing trade in energy carriers

The historical trade in energy carriers was estimated as proportion of the physical trade balance in the materials flows database[1] (MFD) to primary energy consumption derived from the BP World Review 2018[2]. Trade data is not fully consistent in the MFD (i.e. imports and exports do not add up to 0) according to a personal communication with Mirko Lieber[3], who is responsible for the MFD database. We used positive net trade, i.e. net imports, as proxy for trade. The underlying data in the MFD contains primary as well as secondary energy carriers[3] – the respective list is shown in Supplementary Table 1. The MFD however reports these products aggregated to just four categories (Coal, Natural Gas, Oil shale and tar sands, Petroleum). Traded quantities as given in the MFD were converted to the same unit and then the proportion of traded volumes to total primary energy consumption was calculated. Regional aggregation was done according to the table *data/figure1_countries_regions.xlsx* in the Github repository. Supplementary Table 2 gives an overview of aggregated regions.

Trade scenarios

Scenarios for future trade were taken from the IPCC 1.5D Report Scenario Explorer[4] database (IPCC 1.5D) and trade shares were calculated as described above. We have chosen scenarios from the database which fulfill the following two conditions: (1) the proportion of renewable energy generation to primary energy use is larger than 60% (higher shares lead to a reduction in scenarios. This can be assessed with the help of the script), and (2) the calibrated share of trade in 2010 in the scenarios is within 5 percentage points of the observed trade share. The second condition is used to exclude scenarios where observed trade in energy carriers in the models is far off from our observed trade values.

Supplementary Table 1: Considered trade products in the MFD and IPCC 1.5D. The MFD does not report all product categories, but aggregates them to Coal, Natural Gas, Oil shale and tar sands, and Petroleum.

MFD[3]	**IPCC 1.5D**[4]
Primary energy carriers	
	Biomass
Brown Coal, Hard Coal, Lignite, Other Bituminous Coal	Coal
Natural Gas	Natural Gas
Crude Oil, Crude/NGL/Feedstocks, Oil shale and oil sands	Oil
Secondary energy carriers	
42 fossil fuel based products (oil derivatives, coal products, gas products)+	Biomass liquids
	Hydrogen

+ For a full list, contact the authors.

Supplementary Table 2: Regions in scenarios.

Region name	Abbreviation in IPCC_1.5D
Middle East & Africa	R5MAF
Countries of Former USSR	R5REF
Asia & Pacific	R5ASIA
Europe, USA, Canada	R5OECD90+ EU
Latin America	R5LAM
Rest of World	R5ROWO

Table 1: Land-use efficiencies of renewables

To compute land-use efficiencies in Table 1, we developed an excel sheet. It is available in the github repository at *table/table1_calculation_data.xlsx.*

We compare average productivities of different renewable energy carriers for the case of Brazil. We chose Brazil as it is the second largest producer of biofuels globally[2] and has excellent production conditions for biomass as well as wind power plants and solar PV. Sugar-cane and oil palm productivities are literature based, while PV and wind productivities per hectare are derived (1) from estimates of direct land-use of PV and wind power from literature and (2) from average solar and wind productivity in Brazil, as derived from the Brazilian electricity system operator ONS. We calculated minimum and maximum scenarios (if several distinct values were found for the same parameter) and report both values in the final table.

Conversion efficiencies from one energy carrier to another one (e.g. from electricity to gas or fuels) are derived from literature. Land-use for generating electricity for direct CO_2-Capture from air is taken into account (assuming the respective electricity generation technology is also used for direct air capture). Direct land-use of CO2-capture devices are factored in, but estimates are uncertain and are based on Keith et al.[5] and a personal communication with the authors.

Figure 2: Energy use and renewable generation for selected regions

Details on how figure 2 was generated can be found in the R-script *scripts/02_reFUEL_Figure2.R.*

Figure 2 was created by deriving energy use per area, which is the ratio of annual primary energy use to land area, as well as wind power, photovoltaics, and hydro power generation per area which was calculated by summing up the respective electricity generation and dividing by land area. We plot primary energy use per area on the x-axis and renewable energy generation per area on the y-axis. Additionally, we show the share of the region in global energy use (size of the points) and the share of the region in global land area (as color of the points). The data sources used are shown in Supplementary Table 3.

Supplementary Table 3: Data sources used for Figure 2.

Data	Source	Link
Land area	World Bank	http://api.worldbank.org/v2/en/indicator/AG.LND.TOTL.K2?downloadformat=excel
Primary Energy Demand &	BP World Revie	https://www.bp.com/content/dam/bp/en/corporate/excel/energy-economics/statistical-review/bp-stats-review-2018-all-data.xlsx

Renewable Electricity Generation	w 2018

Figure 3: Costs of renewable energy systems

Details on how figure 3 was generated can be found in the R-script *scripts/03_reFUEL_Figure3.R*.

We have collected information about average costs of electricity systems with different shares of variable renewables (VRES) from three different European modelling studies and in total eight scenarios. The studies provide costs in the period 2035-2050. The detailed results of these studies can be found in the accompanying file *data/figure3_data.csv*. Some publications reported the renewable share including curtailment[6,7], others without[8]. We therefore calculated the approximate net VRES share removing curtailed renewables from renewable generation and report the costs while increasing renewable shares by steps of 20% (i.e. from 0% to 100% renewables in 20% steps).

A technology that replaces VRES competes with the marginal difference in costs between different shares of VRES. We calculate these marginal costs as

$$margLCOE = \frac{dSC(p)}{dp} + SC(0)$$

where $margLCOE$ are marginal costs of adding renewables to the system, p is the share of renewables in the system (between 0% and 100%) and $SC(p)$ are average system costs per unit of electricity generated. $SC(0)$ are average system costs without any VRES. This calculation follows Reichenberg et al. [8].

The shown costs of renewable fuel alternatives are based on costs for methane produced from photovoltaics and wind power electricity and direct air capture of CO_2 in the Maghreb region in the year 2040, assuming a capital cost of 5%. This yields costs of around 68 € MWh^{-1}, including transportation to Europe, according to Fasihi et al.[9]. The methane has to be converted to electricity in a power plant. We assume an efficiency of 60%[10] in a combined-cycle power plant, thus yielding final costs of around 115 € $MWh_{electricity}^{-1}$. We further assume that power plants are already installed, therefore not causing any additional capital costs, and that fixed running costs can be covered by the by-product heat.

References

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