A new perspective on global renewable energy systems: why trade in energy carriers matters

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Abstract

Recent global modelling studies suggest a decline of long-distance trade in energy carriers in future global renewable energy systems, compared to today's fossil fuel energy system. In contrast, we identified four crucial drivers that enable trade of renewable energy carriers. These drivers could make trade remain at current levels or even increase during the transition to an energy system with very high shares of renewables.

First, new land-efficient technologies for renewable fuel production become increasingly available and technically allow for long-distance trade in renewables. Second, regional differences in social acceptance and land availability for energy infrastructure support the development of renewable fuel import and export streams. Third, the economics of renewable energy systems, i.e. the different production conditions globally and the high costs of fully renewable regional electricity systems, will create opportunities for spatial arbitrage. Fourth, the reduction of stranded investments in the fossil fuel sector is possible by switching from fossil fuel to renewable fuel trade in exporting regions.

The impact of these drivers on trade in energy carriers is currently under-investigated by the global energy research community. Therefore, we call for a major research effort in this field, in particular as trade can redistribute profits and losses of climate change mitigation and may hence support finding new partners in climate change mitigation negotiations.

The transition to a low carbon energy supply is possible with a range of technologies such as carbon capture and storage, nuclear energy, and renewable energies, according to recent studies with integrated assessment models (IAM). Consistently, those IAM long-term scenarios that have shares of above 60% of renewable energies in the global energy mix in 2100, show a decline in long-distance trade in energy carriers (Figure 1). In 2015, trade in fossil fuels between six major regional groups, i.e. Africa & Middle East, Asia, Europe & North America, Former Soviet Union, Latin America & the Carribean, and Rest of World, amounts to a share of around 23% of global primary energy use*. Trade in the year 2100 declines to below 15% in 43 out of 44 scenarios. Mainly, this is a consequence of less fossil fuels in the supply mix. The long-distance trade of biofuels, wind or solar energy based hydrogen, or electricity – if considered – does not alter this trend. Consistently, the IAM modelling community therefore assumes that a global renewable energy system relies less on long-distance trade in energy carriers than today's fossil fuel system, at least in relative shares.

In contrast, we identified four drivers of long-distance trade in a global renewable energy system. These are linked to new technologies, social acceptance and associated land availability, economics of renewable energy systems, and the continued use of potentially stranded investments in the fossil fuel sectors. Despite uncertainties in the future development of these drivers, we believe that a major effort in the energy research community is necessary to better understand possible future trajectories of global energy systems.

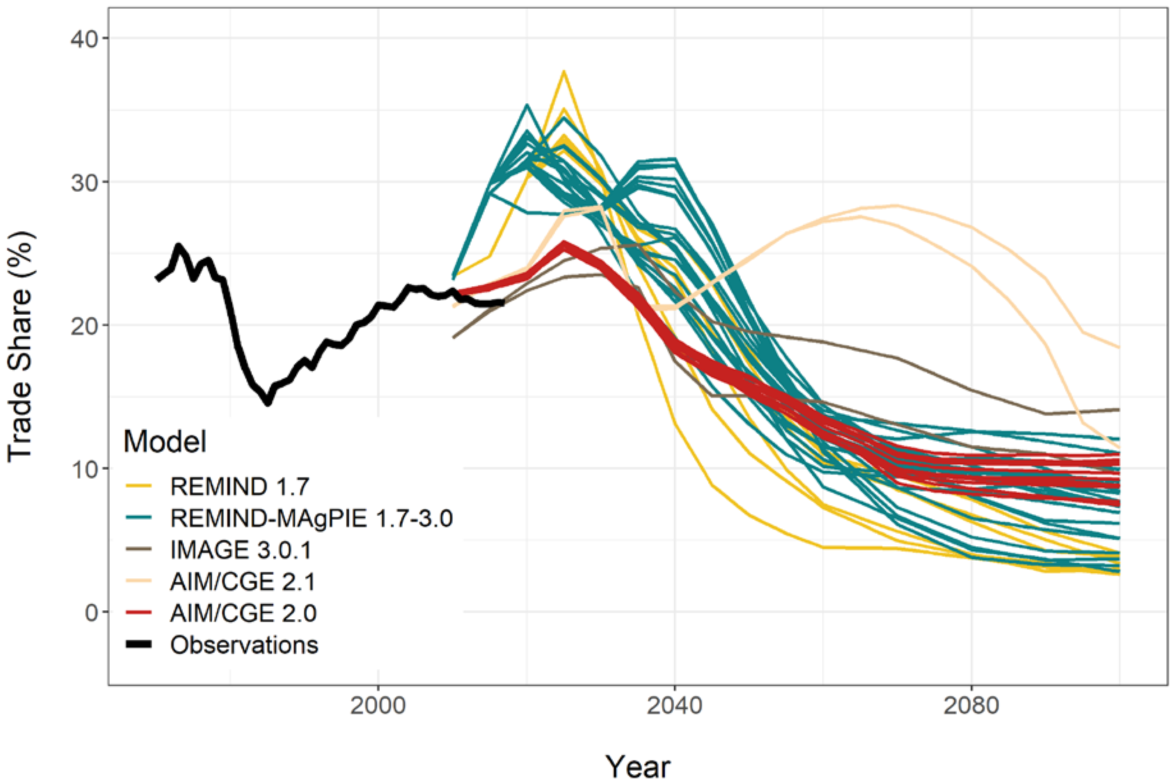

Figure 1: Long-distance trade in primary and secondary energy carriers between six aggregated world regions as share of global primary energy use. The black line shows historical observations of fossil fuel trade[2,3]. The coloured lines refer to 44 different IAM scenarios[4]. All scenarios have a share of renewable energies in primary energy use above 60% and are in the range of 5 percentage points of the observed trade share in 2010. See appendix for details.

* Biomass and biofuels trade is not accounted for. In 2015, the share of these energy carriers in long-distance trade was, however, less than 1% of primary energy use[1].

Driver 1: New technologies for producing renewable energy carriers

New technologies will facilitate the future long-distance trade in renewable energy carriers. Such trade requires either installing inter-continental electricity grids for transmission of renewable electricity, or producing renewable fuels and transporting them with existing liquid or gaseous fuel infrastructure. Transmission grids allow economic benefits for trade over mid-range distances, e.g. between North-Africa and Europe. However, long-distance trade, e.g. between Europe and the US, needs a decrease of transmission costs by a factor of 5 to make it economically profitable[5]. As transmission grids are a mature technology, significant cost reductions of this order of magnitude are questionable.

In contrast, liquid and gaseous fuels do not require installing new infrastructure. Currently, the only technically mature, large-scale option for long-distance trade in renewable energy carriers are biomass-based fuels, i.e. biofuels. Yet, biofuels can sustainably replace only a minor share of fossil fuels in existing global energy systems, as photosynthesis has low solar energy to fuel efficiency[6]. This results in high land requirements and an associated reduction in natural carbon stocks due to land-use change and land management[7].

New technologies for renewable fuel production, such as hydrogen produced from renewable electricity and possibly upgraded to methane or methanol, are associated with significantly lower direct land impacts. For instance, a process that derives hydrogen from electrolysis, using electricity from wind power (WP), and CO_2 directly captured from air, could produce between 410 GWh and 680 GWh km^{-2} a^{-1} of methanol. In contrast, one of the most land-efficient biomass technologies which is commercially available, i.e. palm oil, can only produce around 6 to 7 GWh km^{-2} a^{-1} of biofuel (Table 1). The high land efficiencies of new renewable fuel technologies make impacts on natural carbon stocks in the vegetation negligible. In addition, these technologies allow for production on land with very low carbon stocks, such as semi-arid regions or even deserts. They are therefore effective technologies in terms of climate change mitigation.

An essential ingredient for most of these new renewable fuel technologies is hydrogen. It can be produced via electrolysis[8], photolysis[9], or hydrogenases by bacteria[10]. Hydrocarbons and other fuels can in turn be synthesised from hydrogen and a suitable carbon source through hydrogenation[11], or generated photo-chemically from solar light, water, and carbon[6]. If the CO_2 is captured from the atmosphere[12], these fuels are carbon-neutral. All of these technologies are still under development and not commercially deployed, with the exemption of hydrogen production through electrolysis, which is commercially available although still at low deployment levels globally[13]. For the further analysis, we focus on renewable fuels produced through electrolysis of water, assuming that the electricity is generated from wind, water, and solar energy (WWS), in particular Photovoltaics (PV), WP, and hydropower. We call them WWS fuels in the following. Yet, our reasoning is also applicable to other renewable fuel technologies with high land-use efficiencies.

Logistics does not constitute a major barrier to international trade of renewable fuels[14]. Methane can be traded globally with existing pipeline or liquefied natural gas infrastructure, while methanol and other liquid fuels can be traded and distributed with the current infrastructure for fossil fuels[15]. Hydrogen is currently not liquefied for overseas transportation, despite liquefaction of hydrogen being a long known process[16]. At the current level of technological development, energy needs and costs related to hydrogen liquefaction remain too high for commercialization. Yet, preliminary estimates of future costs allow to assume that in the future the full costs of renewable hydrogen including transportation can become cost-competitive with renewable methane[13,17]. Therefore, new low-cost synthetisation methods for hydrogen, methanol, and methane, based on renewable energies, will increase the opportunities for long-distance trade of renewable fuels.

Table 1: Energy generation per area for renewable fuels assuming Brazilian production characteristics. We use direct impacts on land for the estimation. For details, see appendix.

Resource	Process	Product*	Energy generation per area ($GWh\ km^{-2}\ a^{-1}$)+	
			Lower bound	*Upper bound*
		Commercially available technologies		
Palm Oil	Transesterification	Biodiesel	6.0	7.0
Electricity - Photovoltaics (PV)	Electrolysis	H_2	35	110
Electricity - Wind Power (WP)	Electrolysis	H_2	640	1000
Sugar Cane – 1st Generation	Fermentation	Ethanol	3.0	4.0
		Technologies under development		
Algae	Transesterification	Biodiesel	13	13
Eucalyptus	Gasification and Methane Synthesis	Methane	11	12
Eucalyptus	Gasification and Methanol Synthesis	Methanol	8.9	9.9
Electricity - PV and $CO_2$$	Electrolysis and Methanation	Methane	26	78
Electricity - PV and $CO_2$$	Electrolysis and Methanol Synthesis	Methanol	26	76
Electricity – WP and $CO_2$$	Electrolysis and Methanation	Methane	470	700
Electricity – WP and $CO_2$$	Electrolysis and Methanol Synthesis	Methanol	470	680
Sugar Cane - 2nd Generation	Fermentation and Gasification of Bagasse	Ethanol	7.0	7.0

+ We assume direct impacts of technologies on land as an indicator of land-uptake and competition with agriculture and forestry. The spacing area of wind parks and PV installations, which is more relevant for estimating production potentials, is larger (by two orders of magnitude for wind and by a factor of 2 for PV)[18]. For direct air capture of CO_2, land requirements are considered in the table, but contain a relatively high uncertainty.

* All production processes have different amounts of co-products (primarily heat and/or electricity).

$ CO_2 is assumed to be taken out of the atmosphere using direct air capture.

Driver 2: Social acceptance of renewables and land availability

Significant trade streams in WWS fuels only will be economically competitive and reduce carbon emissions, if some regions produce excess WWS. Currently, this is not the case, as no region is close to producing more WWS than its primary energy use (Figure 2). Therefore, a global renewable energy system will need significant growth in WWS generation everywhere. If growth in WWS generation is faster than growth in energy use in some regions for extended periods, these regions may become able to generate WWS fuels. For example, if future WWS generation per area in Canada or Brazil converges to the current level of WWS generation per area in Germany - at 473 $MWh\ km^{-2}\ a^{-1}$ – a little surplus of WWS fuels for export could theoretically be produced. Currently, WWS generation per area has not converged globally (Figure 2), but late adopters of PV and WP have faster growth in these technologies than early adopters[19].

The growth in renewables is driven by multiple factors such as support policies[20], economic growth, size of the electricity sector, and endowments with physical potentials[19]. Yet, the wide field of assessing land availability is a further important factor, often neglected in studies of energy systems[21]. While most regions in principle have sufficient land available for WWS generation due to low land requirements of WWS fuels (Table 1), a lack of social acceptance associated with the deployment of the associated infrastructure is observed already today in some regions. The relation between social acceptance and density of WWS infrastructure is therefore crucial for understanding their future spatial distribution. Acceptance may remain constant with the penetration level of WWS, if a strong shifting baseline phenomenon[22] in the perception of renewable infrastructure is present. In that case, convergence of WWS generation per area will be low globally, everything else equal, as regions with high energy use will also be able to deploy large amounts of WWS. If, in contrast, conflicts over new projects increase with the penetration level of WWS, the speed of convergence may increase. Trade in WWS fuels can develop under these conditions, as regions rich in land in relation to energy use will face less social conflicts when they increase the level of WWS generation above their level of energy use.

In Europe, which has globally the highest WWS spatial density conflicts due to critical impacts of large-scale infrastructure, in particular wind turbines, on the aesthetic perceptions of landscapes, and on the environment are already observed today[23]. Some conflicts are however also related to trust, and planning procedures and can be partly mitigated by better sharing of information, by participatory processes in decision making[24], and by procedural justice[25]. Additionally, conflicts also are present in regions with much lower WWS generation per area, such as the United States[26] and Brazil, which is a promising exporting country from the Global South. There, the livelihood of rural populations particularly in the North-East of the country is negatively affected by the rapid expansion of wind parks and, consequently, territorial conflicts are triggered[27]. The evidence does not yet allow to draw clear conclusions with respect to the relation of WWS generation per area and social acceptance therefore. In regions where WWS generation per area is much lower than in e.g. Europe, it seems, however, theoretically possible to mitigate those impacts at lower costs, if institutional capacities to deal with emerging conflicts are built-up.

We conclude that one core aspect in understanding the future spatial distribution of WWS generation infrastructure is land availability and associated conflicts regarding access to and control over land. Existing theories of land-use change[25] do not address the role of WWS generation infrastructure in the competition for land. Accordingly, the most widely applied modelling approaches for future global energy systems do not assess land requirements for WWS generation infrastructure expansion in detail[21]. For understanding the role of trade in globale renewable energy systems, a comprehensive assessment of these processes is, however, crucial and research in this field is therefore of fundamental importance.

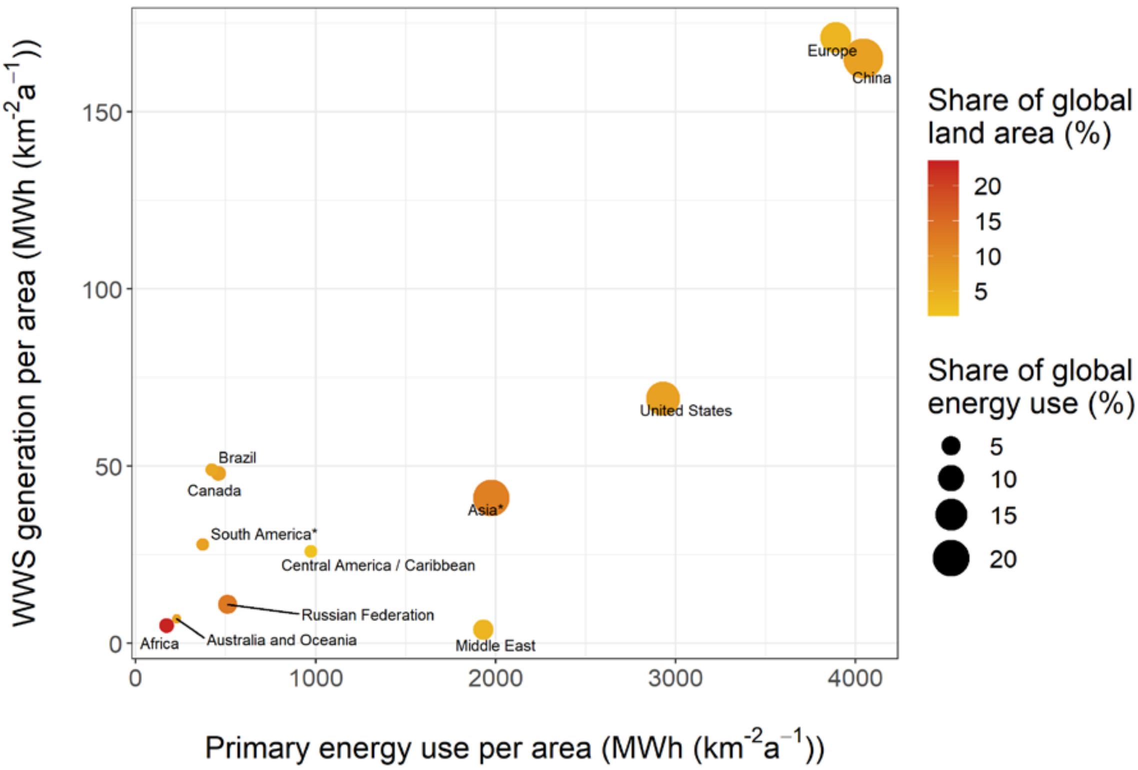

Figure 2: Primary energy use per area plotted vs. current WWS power generation per area. *Single countries also shown in the Figure (i.e. Brazil and China) are not included in the respective regions. See appendix for details. Observation: Primary energy use is a rough indicator for final energy use, as it will likely fall with renewable electrification of most services. Jacobson et al.[28] estimate a reduction of up to around 40% on average for energy systems with high shares of intermittent renewables.

Driver 3: Economics of renewable energy systems

Future energy systems will likely be largely electrified[28]. However, some applications in transportation and industry will require liquid or gaseous fuels as the costs of fully electrifying these applications are prohibitively high. These applications include air transport, trucks, shipping and energy-intensive manufacturing industries[29–32]. Here, renewable fuels, tradable over inter-continental distances and storable at low costs, can provide a low-carbon alternative to electricity to allow deep decarbonisation.

Moreover, renewable fuels could also have beneficial applications in future electricity systems. A series of studies has shown that, in principle, electricity systems with very high shares of variable renewables (VRES, i.e. PV and Wind) are possible on a country or continental level[33–35]. Different technological options in the energy system, such as sectoral integration[36], spatial and technological diversification of VRES generation[35], and integration of different generation and storage technologies[37] allow to operate electricity systems almost fully based on VRES. Yet, the system levelized costs of electricity[38] are lowest at VRES penetration well below 100%[39–41], as depicted in Figure 3. WWS fuels have therefore the potential to lower system costs of highly renewable electricity systems, being a renewable, dispatchable source of electricity generation.

Figure 3 compares marginal system levelized costs of electricity at different shares of VRES from three modelling studies for Europe. The marginal costs of the systems at various penetration levels of renewables are compared to cost estimates of electricity generation from WWS liquid fuels. Using dispatchable generation and reducing the share of intermittent electricity in the system has the potential to reduce system costs significantly and allows for a more efficient use of local VRES[42]. At future cost estimates of electricity generation from WWS fuels, these fuels would be competitive to VRES at a renewable share of about 80% or above in most scenarios (Figure 3).

While renewable fuels have the potential to decrease costs of highly renewable electricity systems, this does not necessarily imply long-distance trade in renewable fuels, as they might be produced locally. Yet, regions with high energy consumption are often not the ones that are best endowed with renewable resources[43]. Moreover, even with the same resource endowment, regions with high energy consumption have to tap deeper into the available resources, meaning that more locations with less favourable conditions have to be accessed, resulting in increasing marginal costs of electricity supply from WWS.

For instance, in Germany, full load hours of PV generation are a third of the best locations in Chile[44]; and hybrid PV-WP systems in Germany remain below 4,000 full load hours, while the same systems can reach more than 6,000 full load hours in some parts of Africa, North and South America, and Asia[43]. Other factors, such as available infrastructure, regulation, labour, land and capital costs[45], also influence the economics of renewable fuel projects. In consequence, differences in levelized cost of electricity between regions may be smaller than bio-physical differences would imply. For the example of Chile, production costs are only half of those in Germany[46], despite three-fold full load hours.

Global cost differences in the production of renewable fuels together with comparatively low transportation costs of renewable fuels (see Driver 1) make long-distance trade in renewable fuels economically viable. Such an undertaking would have the additional benefit of decreasing climate change mitigation costs, thereby fostering support for the necessary transition.

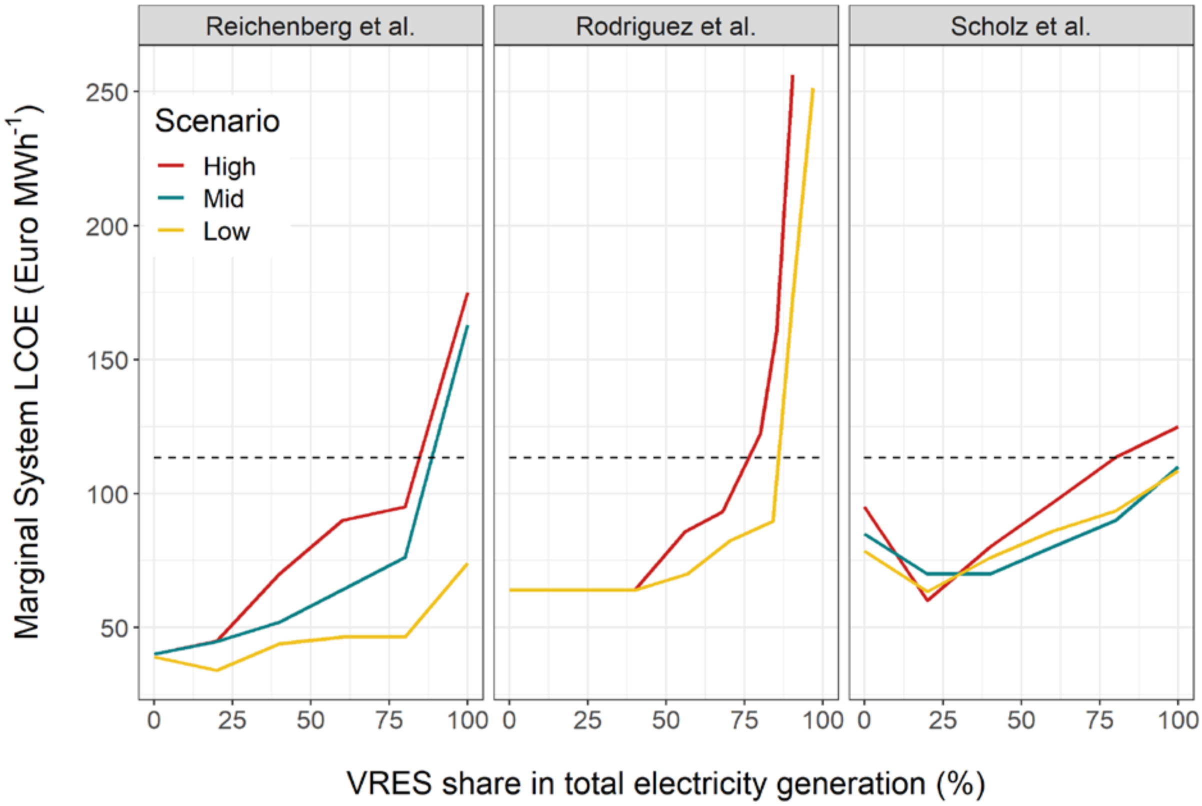

Figure 3: Marginal system levelized costs of electricity (LCOE) for varying levels of VRES in total generation for different scenarios in three different modelling studies[39–41] (coloured lines) compared to lower bound for costs of generating electricity from WWS diesel[16] (black dashed line). Scenarios are derived for the period 2035-2050. Marginal System LCOE are calculated according to Reichenberg et al.[41]. See appendix for details.

Driver 4: Reduction of stranded investments in fossil fuel sectors

The current fossil fuel energy system, consisting of infrastructure, institutions, and behaviour, is a major factor to lock our societies into a high-carbon world[47]. In particular coal and gas power plants, as well as oil fuelled vehicles, are substantial infrastructure assets that increase the lock-in effect[48]. Actors who produce, process and transport fossil fuels face the risk of huge stranded investments due to a full decarbonization of energy systems in the coming decades[49]. This causes lower incentives and weak commitments to mitigate climate change. Such stranded investments could be partly avoided if the existing infrastructure serves as a bridge to a low-carbon world. A sufficiently large renewable fuel sector will allow such continued use of adapted fossil fuel infrastructure, i.e. for transportation and distribution, and for end uses.

Nevertheless, if renewable fuels are deployed at large scale, stranded investments will remain high for fossil resource owners. The largest owners of unburnable resources under strong climate change mitigation are China and India, Russia, the Middle East, and the US[50]. These regions may, however, benefit from new opportunities arising with the use of renewable fuels, as they are endowed with substantial potential for renewable fuel production[43]. To some extent, income, generated from renewable fuel exports, may offset the cost of abandoning fossil fuel extraction. Hence, existing regional specialization in energy carrier production, e.g. as in the Middle East, may remain due to local sectoral lock-in effects, consequently increasing trade flows.

Conclusions

The four drivers indicate current gaps in understanding the role of long-distance trade in a global renewable energy system. We believe closing these gaps will assist in solving the challenges on the way to a sustainable low-carbon world. In particular, trade scenarios may help in closing future climate change mitigation deals, as a global energy system incorporating renewable fuels will redistribute the gains and losses from the projected measures to mitigate climate change. They may therefore potentially increase acceptance by actors involved in the production, transportation, or consumption of fossil fuels, who currently oppose strong global mitigation efforts.

Nevertheless, important limitations associated with scenarios of trade in renewable fuels that range from the development of global trade and climate change agreements, to uncertain technological developments, and future forms and positioning of politics to steer energy transitions and energy democracy, have to be taken into account. Also significant normative questions play a role: the valuation of local impacts of different generation and production technologies in different world regions, concerns with security of supply, and the public opinion on trade have to be better understood and considered in scenarios. However, to largely neglect the factor trade in future global energy scenarios risks reducing the visibility of options to reach climate change mitigation targets. We call for an extended research effort into future renewable fuel trade scenarios in the energy research community therefore, as closing the research gaps requires a major effort in improving existing modelling tools, theories, and data sets.

Acknowledgements

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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 *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 *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 *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 & Renewable Electricity Generation	BP World Review 2018	https://www.bp.com/content/dam/bp/en/corporate/excel/energy-economics/statistical-review/bp-stats-review-2018-all-data.xlsx

Figure 3: Costs of renewable energy systems

Details on how figure 3 was generated can be found in the R-script *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 *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 diesel 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.

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