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OPINION

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

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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 based system. In contrast, we identify four drivers that facilitate trade of renewable energy carriers. These drivers may lead to trade volumes remaining at current levels or even to an 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, a reduction of stranded investments in the fossil fuel sector is possible by switching from fossil fuels to renewable fuel trade. The impact of these drivers on trade in renewable energy carriers is currently under-investigated by the global energy systems research community. The importance of the topic, in particular as trade can redistribute profits and losses of decarbonization and may hence support finding new partners in climate change mitigation negotiations, warrants further research efforts in this area therefore.

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Broader context

Mitigating climate change requires a global transition towards energy systems with low or even negative greenhouse gas emissions. While there are multiple options to design such systems, reaching very high shares of electricity generation from renewable sources is frequently considered to be among the best available ones. Scenarios of such a global transition, summarized for example by the Intergovernmental Panel on Climate Change, indicate a decline in intercontinental trade in energy carriers as electricity generation from renewable sources increases. In other words, highly renewable energy systems are foreseen to be largely regional. This, however, is not necessarily the case. Quite contrary, intercontinental trade in renewable solar and electric fuels may become a major option in the coming decades. Our article presents four main drivers of this development related to new technologies, regional differences in social conflicts related to renewable energy infrastructure, the economics of renewable energy systems, and the possible continuation of the use of otherwise stranded fossil fuel infrastructure. The development of global renewable fuel trade streams may cause unintended social, technical, and economic consequences. We therefore call for a major research effort to increase our understanding of an energy future with high shares of renewable fuel trade.

Introduction

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) published in the latest IPCC report on limiting global temperature increases to 1.5 °C.[1] IAMs are used to study the long-term development of our economies under climate change mitigation pathways. The energy sector, as a major emitter of greenhouse-gas emissions, is modelled in detail in most IAMs. IAM long-term scenarios with a renewable energy share above 60% of global primary energy

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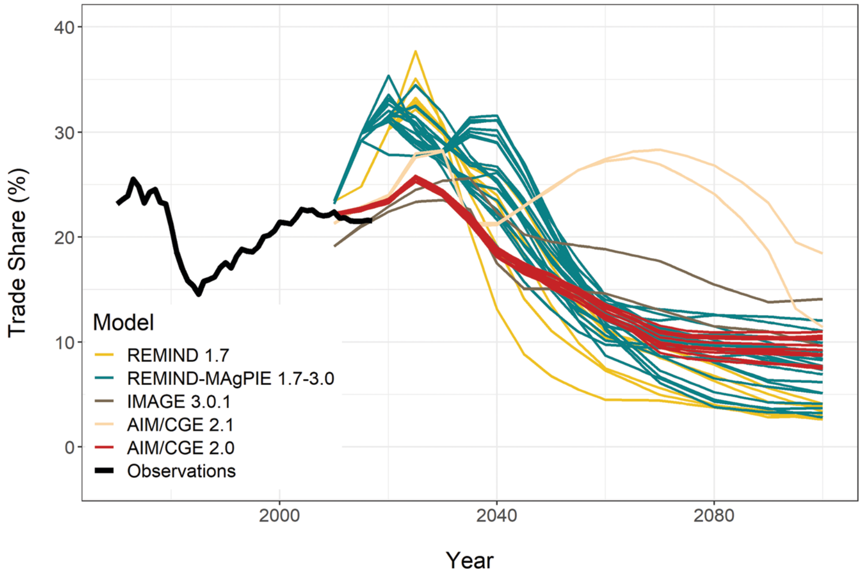

Fig. 1 Long-distance trade in primary and secondary energy carriers between six aggregated world regions as share of global primary energy use. The black line shows historical observations of fossil fuel trade.[5,6] The coloured lines refer to 44 different IAM scenarios.[7] All scenarios have a share of renewable energies in primary energy use above 60%. See appendix for details.

consumption by 2100 consistently show a decline in long-distance trade in energy carriers (Fig. 1). In 2015, the observed trade in fossil energy carriers 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 IAM scenarios. This is a consequence of a relative decline in both the use of fossil fuels and the associated trade as well as a mostly regionalized production of renewable energies. The long-distance trade of biofuels, hydrogen derived from wind or solar energy, or electricity is not even considered in many of the scenarios. Moreover, even for the scenarios which assess trade in renewable fuels, trade shares remain low. These findings in the IPCC scenarios are consistent with a range of other published IAM assessments.[2–4] At the moment, 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 identify four drivers that facilitate 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. In the following, we give an overview of these drivers and identify important research gaps.

Driver 1: new technologies for producing renewable energy carriers

New technologies will enable future long-distance trade in renewable energy carriers. Such trade either requires installing inter-continental electricity grids for transmitting renewable electricity or producing renewable fuels and transporting them with (existing) liquid or gaseous fuel infrastructure. Electricity transmission grids allow economic benefits for trade over mid-range distances, *e.g.* between North-Africa and Europe. However, long-distance electricity transmission, *e.g.* between Europe and the US, needs a decrease of transmission costs by a factor of 5 to make it economically viable.[8] Yet, transmission grids are a mature technology, rendering significant cost reductions of this order of magnitude questionable.

In contrast, liquid and gaseous fuels would allow for the re-use of existing trade infrastructure. Currently, the only technically mature, large-scale option for long-distance trade in renewable energy carriers are biomass-based fuels, *i.e.* biofuels. However, biofuels can sustainably replace at best a minor share of fossil fuels in existing global energy systems, as photosynthesis has low solar energy to fuel conversion efficiency.[9] This results in high land requirements and, in turn, in an associated reduction in natural carbon stocks due to land-use change and land management.[10] New technologies for renewable fuel production, such as the production of hydrogen from water electrolysis based on renewable electricity along with a potential upgrade to gaseous or liquid carbon-based fuels, are associated with significantly lower direct land impacts. For instance, a process that derives hydrogen from electrolysis, using electricity from wind power (WP), and carbon dioxide directly captured from air,[11] could produce between 410 GW h km^{-2} a^{-1} and 680 GW h 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 GW h 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 therefore. In addition, these technologies allow for fuel production on

‡ 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.[70]

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

			Energy generation per area[b] (GW h km^{-2} a^{-1})	
Resource	Process	Product[a]	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[c]	Electrolysis and methanation	Methane	26	78
Electricity – PV and CO_2[c]	Electrolysis and methanol synthesis	Methanol	26	76
Electricity – PV and nitrogen[c]	Electrolysis, ammonia synthesis, and ammonia cracking	H_2 through ammonia	22	59
Electricity – WP and CO_2[c]	Electrolysis and methanation	Methane	470	700
Electricity – WP and CO_2[c]	Electrolysis and methanol synthesis	Methanol	470	680
Electricity – WP and nitrogen[c]	Electrolysis, ammonia synthesis, and ammonia cracking	H2 through Ammonia	410	550
Sugar cane – 2nd generation	Fermentation and gasification of bagasse	Ethanol	7.0	7.0

[a] 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).[12] For direct air capture of carbon dioxide, land requirements are considered in the table, but contain a relatively high uncertainty. The energy requirement for direct air capture is in the range of 5–9% of the final product energy content. [b] All production processes have different amounts of co-products (primarily heat and/or electricity). [c] Carbon dioxide and Nitrogen are assumed to be taken out of the atmosphere using direct air capture.

land with very low potential natural carbon stocks, *i.e.* potential vegetation, such as semi-arid regions or even deserts. They are therefore effective technologies in terms of climate change mitigation.

Land-efficient renewable fuels can be broadly classified into power-to-fuel technologies[13,14] and solar fuel technologies.[9,15] Power-to-fuel technologies use electricity, generated by any available renewable power generation technology, for electrolysis of water[16] or carbon dioxide[17] with potential subsequent upgrades to methane[18] or liquid fuels.[14,19] In contrast, solar fuel technologies produce renewable hydrogen or carbon based fuels directly from solar light, water, and/or carbon dioxide using thermo-chemical[20–22] or photo-electro-chemical[15,23,24] processes.

If the carbon dioxide is captured from the atmosphere,[25] these fuels are carbon-neutral. All of these technologies are still under development, not competitive on markets,[26] and therefore not yet commercially deployed. The exemption is hydrogen production through electrolysis, which is commercially available although still at low deployment levels globally.[27] By 2050, however, pure renewable hydrogen production and Fischer–Tropsch synthesis of diesel from renewable hydrogen and carbon dioxide are estimated to become cost-competitive to their fossil counterparts.[26]

Logistics and distribution do not necessarily constitute major barriers to international trade of renewable fuels[28] as some renewable fuels such as renewable methane and renewable diesel are direct replacements of their fossil equivalents. For other carbon-based fuels such as ethanol, methanol, and dimethyl-ether (DME), however, the current infrastructure would have to be adapted to some degree. Utilizing hydrogen, purely or stored in chemical compounds such as methanol or ammonia, needs even more infrastructure adaptation, both regarding transportation and distribution, and regarding applications and final use.[29,30] Today, hydrogen is not liquefied for overseas transportation at large scale, despite liquefaction of hydrogen being a long known process.[31] Even though, first demonstration projects for overseas shipping of hydrogen are underway.[32] Yet, at the current level of technological development, energy needs and costs related to hydrogen liquefaction prohibit large-scale commercialization. Current estimates of future costs, however, show that the full costs of renewable hydrogen including long-distance transportation can become cost-competitive with renewable methane in the medium-term,[27,32] in particular if hydrogen is stored in non-carbon fuels such as ammonia.[30,33,34] 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.

In our further analysis, we focus on renewable fuels produced through electrolysis of water, assuming that the electricity is generated through photovoltaics (PV), windpower (WP), and hydropower. We refer to such fuels as 'WWS fuels'. Our reasoning is in principle also applicable to non-electricity based solar-fuel technologies with high land-use efficiencies, although there are differences in terms of their integration into the energy system: while both, power-to-fuel and solar-fuel products can be used in electricity generation, only power-to-fuel technologies consume electricity from the grid, thus offering potential for demand-side flexibility.

Driver 2: social acceptance of renewables and land availability

Significant trade streams in WWS fuels will be economically competitive and reduce carbon emissions only, if some regions produce surplus WWS. Currently, this is not the case, as no

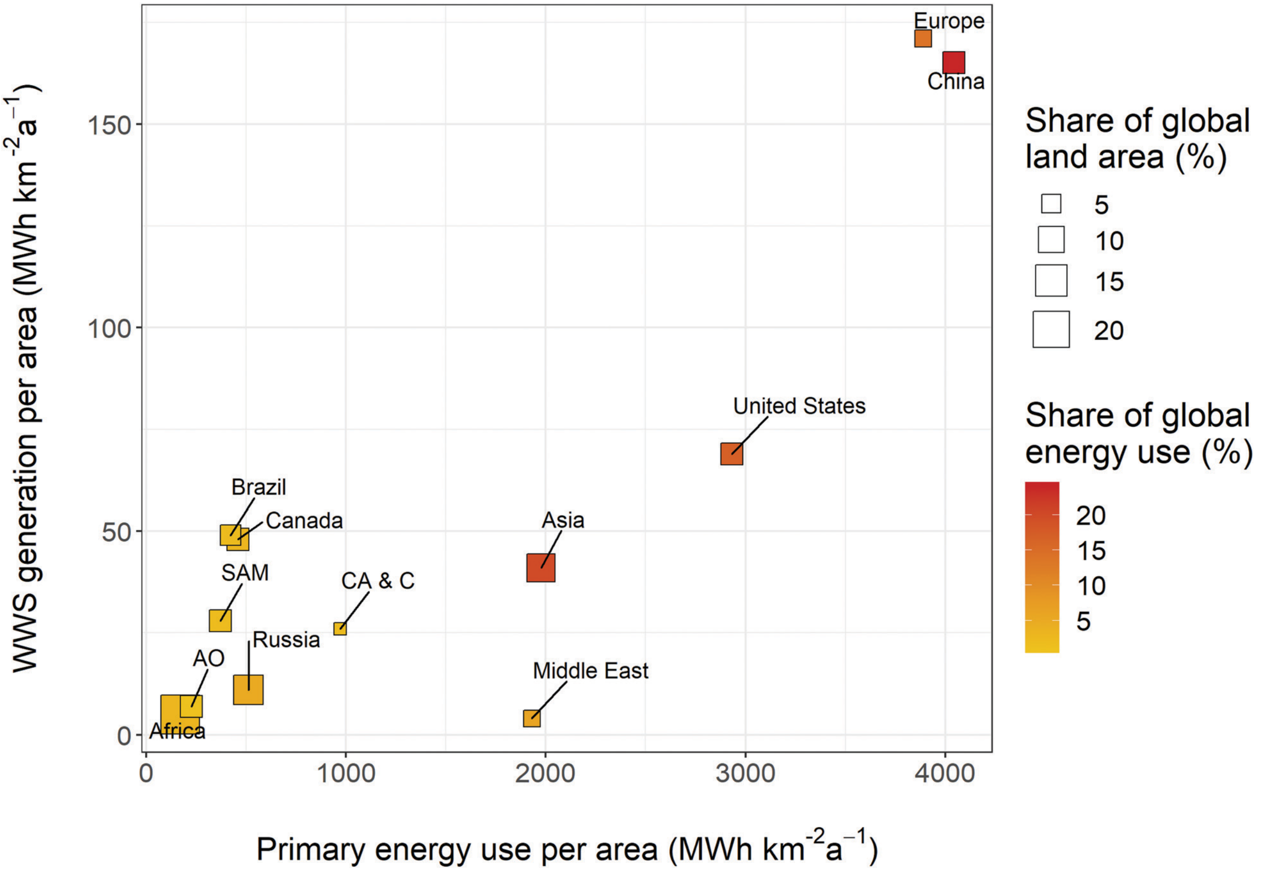

Fig. 2 Primary energy use per area plotted *vs.* current WWS power generation per area. Single countries shown in the figure (*i.e.* Brazil and China) are not included in the respective regions. SAM: South America, AO: Australia & Oceania, CA & C: Central America & Caribbean. See appendix for details. 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.*[44] estimate a reduction of up to around 40% on average for energy systems with high shares of intermittent renewables.

global region is close to producing more WWS than its primary energy use (Fig. 2). Therefore, a global renewable energy system will require 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 generate surplus 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 MW h km^{-2} a^{-1} – a surplus of WWS fuels could be exported. Currently, WWS generation per area has not converged globally (Fig. 2), but late adopters of PV and WP experience faster growth in these technologies than early adopters.[35]

The growth in renewable generation is driven by multiple factors such as support policies,[36] economic growth, size of the electricity sector, and endowments with physical potentials.[35] Yet, the availability of land is a further important factor, often neglected in studies of energy systems.[37] 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 WWS infrastructure is already observed today in some regions.[38] 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[39] in the perception of renewable infrastructure is present. In that case, convergence of WWS generation per area is likely to 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 is likely to increase. Trade in WWS fuels can develop under these circumstances, 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 the highest WWS spatial density globally, 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.[38] 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,[40] and by improving procedural justice.[41] Additionally, conflicts are also present in regions with much lower WWS generation per area compared to Europe, such as the United States[42] and Brazil, which is a promising exporting country from the Global South. The livelihood of rural communities particularly in the North–East of Brazil is negatively affected by the rapid expansion of wind parks and, consequently, territorial conflicts are triggered.[43] The evidence does thus not yet allow for drawing clear conclusions with respect to the relation between WWS generation per area and social acceptance. In regions where the 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 a 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[45] 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.[37] For understanding the role of trade in global renewable energy systems, a comprehensive assessment of these processes is, however, crucial and research in this field is therefore of fundamental importance.

Driver 3: economics of renewable energy systems

Future energy systems will likely be electrified to a large extent.[44] 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.[46–49] 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.[50–52] Different technological options in the energy system, such as sectoral integration,[53] spatial and technological diversification of VRES generation,[52] and integration of different generation and storage technologies[54] allow for operation of electricity systems almost fully based on VRES. Yet, the system levelized costs of electricity[55] are lowest at a VRES penetration well below 100%,[56–58] as depicted in Fig. 3. WWS fuels thus have the potential to lower system costs of highly renewable electricity systems, being a renewable, dispatchable source of electricity generation.

Fig. 3 shows 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 introducing

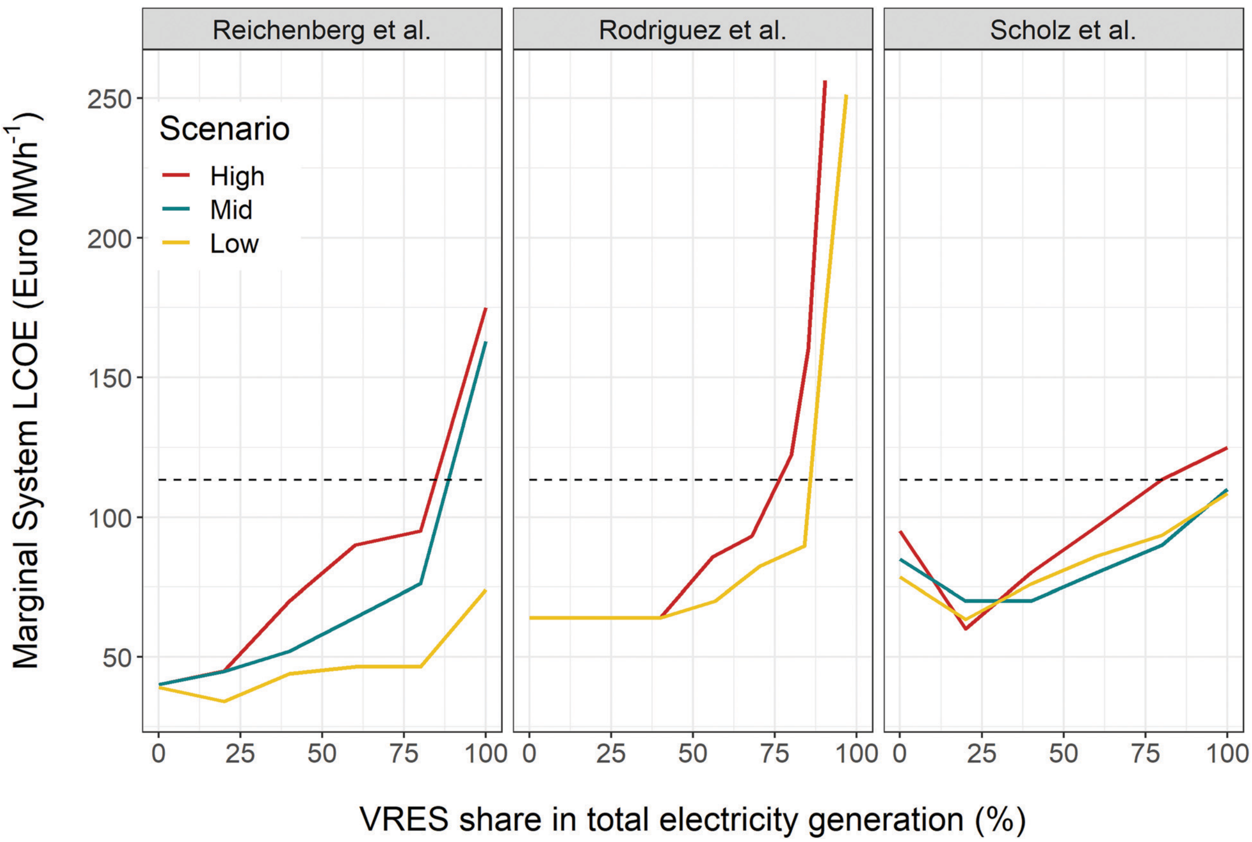

Fig. 3 Marginal system levelized costs of electricity (LCOE) for varying levels of VRES in total generation for different scenarios in three different modelling studies[56–58] (coloured lines) compared to lower bound for costs of generating electricity from WWS methane[28] (black dashed line). Scenarios are derived for the period 2035–2050. Marginal System LCOE are calculated according to Reichenberg *et al.*[58] See appendix for details.

some electricity generation from WWS methane, the lowest cost option compatible to current electricity generation infrastructure. For WWS methane powered electricity generation, we only took into account variable costs, as the necessary power generation infrastructure is already in place today in many world regions. We chose WWS methane for the comparison, as it can easily substitute fossil methane in power generation, while other renewable liquid or gaseous fuels would require installing new generation facilities.

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.[59] 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 (Fig. 3).

While we have demonstrated that renewable fuels have the potential to decrease the 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 use are often not the ones that are best endowed with renewable resources.[19] Moreover, even with the same resource endowment, regions with high energy use 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;[60] and hybrid PV–WP systems in Germany remain below 4000 full load hours, while the same systems can reach more than 6000 full load hours in some parts of Africa, North and South America, and Asia.[19] Other factors, such as available infrastructure, regulation, labour, land and capital costs,[61] 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,[62] despite three-fold full load hours. Still, these cost differences may allow for trade of renewable fuels between Chile and Germany. Another example of the possibilities of spatial arbitrage are solar-radiation and land-rich Australia, on the one hand, and high energy demanding East-Asia, on the other hand.[63]

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.

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.[64] In particular coal and gas power plants, as well as oil fuelled vehicles, are substantial infrastructure assets that increase the lock-in effect.[65] 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.[66] This causes weaker incentives and less 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 would 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 fossil resources, which should not be burned under strong climate change mitigation, are China and India, the Former Soviet Union countries, the Middle East, and the US.[67] 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.[19] Using these resources to generate exportable renewable fuels would help to offset the cost of abandoning fossil fuel extraction to some extent. As a consequence, the prevailing regional specialization in energy commodity production, as for example in the Middle East, might well remain, supporting energy trade flows also in the future.

Discussion & conclusions

We have presented four drivers of trade in renewable fuels in global energy systems with high shares of renewables. These drivers put into question the currently dominating view in the energy system modelling community that renewables expansion will cause a decline in long-distance trade in energy commodities. We have discussed that new, land-efficient ways of producing renewable fuels may become cost-competitive until 2050 and therefore can allow for long-distance trade of renewable energies. If these fuels are made compatible with the existing infrastructure for liquid and gaseous fuels in our current fossil energy systems, *e.g.* by constituting equivalents to fossil diesel, gasoline, or methane, they would allow avoiding stranded costs in the fossil fuel sector. Countries with high energy demand densities additionally have strong incentives for using renewable fuels, as they allow for reduction of the conflicts caused by renewable infrastructure expansion in densely populated regions. Additionally, costs of imported renewable fuels may be lower than local production, as the production costs depend on highly diverse climatic, regulatory, land availability related, and economic conditions.

On the contrary, other factors may hinder the advent of trade in renewable fuels. Deploying renewable energy generators on large scale is incentivised only under strict greenhouse gas emission limits. If the global community cannot agree on far-reaching mitigation measures, renewable energies in general and renewable fuels in particular will account only for a minor share in global energy supply. Also, global and bilateral agreements on freetrade can have a strong impact on the opportunities for trade. Likewise, deployment of renewable energies is often seen as a measure to promote security of energy supply,[2] a formidable goal of energy policy. Yet, trade in renewable fuels may be understood as a continuation of the current dependency on oil and gas exporters by importing countries. Moreover, energy security is relevant also on community level, where many small regions strive for energy autarky.[68] Finally, sourcing renewable fuels from the Global South may cause adverse effects on local populations, as has been observed *e.g.* in biofuel production schemes.[69]

Despite uncertainties in the future development of these drivers, we are convinced that a major effort in the energy research community is necessary to better understand possible future trajectories of global energy systems: a future global, decarbonized energy system depends on decisions we take in the present, as the formation of energy systems is characterised by strong lock-in effects. Today's decisions therefore need to be based on thorough understanding and analysis of available future options, in order to support setting the appropriate political agendas now.

Some of the uncertainties can be narrowed down by improving our understanding of the scientific and technological fundamentals of renewable fuel production, the associated economics along the whole supply chain, social conflicts associated with renewable energy infrastructure expansion, and preferences of actors in the system for open or closed global energy systems. At the same time, some uncertainties cannot be reduced, such as predicting long-term political developments. Therefore, we call on the energy system modelling community to explore these uncertainties much more comprehensively than is the current practice. This will allow deriving new scenarios of global de-carbonization and at the same time support the definition of research and development agendas today. Additionally, demonstrating potential gains from trade might impact the attitude of fossil-fuel locked-in players, thus fostering progress in climate change mitigation negotiations.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

1 J. Rogelj, D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian and M. V. Vilariño, *in Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, IPCC, 2018.

2 J. Jewell, V. Vinichenko, D. McCollum, N. Bauer, K. Riahi, T. Aboumahboub, O. Fricko, M. Harmsen, T. Kober, V. Krey, G. Marangoni, M. Tavoni, D. P. van Vuuren, B. van der Zwaan and A. Cherp, *Nat. Energy*, 2016, **1**, 16073.

3 A. Cherp, J. Jewell, V. Vinichenko, N. Bauer and E. D. Cian, *Clim. Change*, 2016, **136**, 83–94.

4 D. McCollum, N. Bauer, K. Calvin, A. Kitous and K. Riahi, *Clim. Change*, 2014, **123**, 413–426.

5 British Petrol, BP Statistical Review of World Energy 2018, 2018.

6 International Resource Panel, Global Material Flows Database, 2018.

7 D. Huppmann, E. Kriegler, V. Krey, K. Riahi, J. Rogelj, S. K. Rose, J. Weyant, N. Bauer, C. Bertram, V. Bosetti, K. Calvin, J. Doelman, L. Drouet, J. Emmerling, S. Frank, S. Fujimori, D. Gernaat, A. Grubler, C. Guivarch, M. Haigh, C. Holz, G. Iyer, E. Kato, K. Keramidas, A. Kitous, F. Leblanc, J.-Y. Liu, K. Löffler, G. Luderer, A. Marcucci, D. McCollum, S. Mima, A. Popp, R. D. Sands, F. Sano, J. Strefler, J. Tsutsui, D. Van Vuuren, Z. Vrontisi, M. Wise and R. Zhang, *IAMC 1.5 °C Scenario Explorer and Data hosted by IIASA*, Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis, 2018.

8 M. Dahl, R. A. Rodriguez, A. A. Søndergaard, T. Zeyer, G. B. Andresen and M. W. Greiner, in *New Horizons in Fundamental Physics*, ed. S. Schramm and M. Schäfer, Springer International Publishing, Cham, 2017, pp. 333–356.

9 A. K. Ringsmuth, M. J. Landsberg and B. Hankamer, *Renewable Sustainable Energy Rev.*, 2016, **62**, 134–163.

10 K.-H. Erb, T. Kastner, C. Plutzar, A. L. S. Bais, N. Carvalhais, T. Fetzel, S. Gingrich, H. Haberl, C. Lauk, M. Niedertscheider, J. Pongratz, M. Thurner and S. Luyssaert, *Nature*, 2018, **553**, 73–76.

11 F. Creutzig, C. Breyer, J. Hilaire, J. Minx, G. P. Peters and R. Socolow, *Energy Environ. Sci.*, DOI: 10.1039/C8EE03682A.

12 L. M. Miller and D. W. Keith, *Environ. Res. Lett.*, 2018, **13**, 104008.

13 T. M. Gür, *Energy Environ. Sci.*, 2018, **11**, 2696–2767.

14 S. Schemme, R. C. Samsun, R. Peters and D. Stolten, *Fuel*, 2017, **205**, 198–221.

15 T. Faunce, S. Styring, M. R. Wasielewski, G. W. Brudvig, A. W. Rutherford, J. Messinger, A. F. Lee, C. L. Hill, H. deGroot, M. Fontecave, D. R. MacFarlane, B. Hankamer, D. G. Nocera, D. M. Tiede, H. Dau, W. Hillier, L. Wang and R. Amal, *Energy Environ. Sci.*, 2013, **6**, 1074–1076.

16 A. Buttler and H. Spliethoff, *Renewable Sustainable Energy Rev.*, 2018, **82**, 2440–2454.

17 T. Haas, R. Krause, R. Weber, M. Demler and G. Schmid, *Nat. Catal.*, 2018, **1**, 32.

18 K. Ghaib and F.-Z. Ben-Fares, *Renewable Sustainable Energy Rev.*, 2018, **81**, 433–446.

19 M. Fasihi, D. Bogdanov and C. Breyer, *Energy Procedia*, 2016, **99**, 243–268.

20 S. Zhai, J. Rojas, N. Ahlborg, K. Lim, M. F. Toney, H. Jin, W. C. Chueh and A. Majumdar, *Energy Environ. Sci.*, 2018, **11**, 2172–2178.

21 K. Onuki, S. Kubo, A. Terada, N. Sakaba and R. Hino, *Energy Environ. Sci.*, 2009, **2**, 491–497.

22 D. Marxer, P. Furler, M. Takacs and A. Steinfeld, *Energy Environ. Sci.*, 2017, **10**, 1142–1149.

23 Acatech – National Academy of Science and Engineering, Germany National Academy of Sciences Leopoldina, Union of

the German Academies of Sciences and Humanities, Artificial Photosynthesis., German National Academy of Sciences and Humanities., Munich, 2018.

24 A. C. Nielander, M. R. Shaner, K. M. Papadantonakis, S. A. Francis and N. S. Lewis, *Energy Environ. Sci.*, 2014, **8**, 16–25.

25 D. W. Keith, G. Holmes, D. S. Angelo and K. Heidel, *Joule*, 2018, **2**, 1573–1594.

26 R. J. Detz, J. N. H. Reek and B. C. C. van der Zwaan, *Energy Environ. Sci.*, 2018, **11**, 1653–1669.

27 I. Staffell, D. Scamman, A. V. Abad, P. Balcombe, P. E. Dodds, P. Ekins, N. Shah and K. R. Ward, *Energy Environ. Sci.*, 2019, **12**, 463–491.

28 M. Fasihi, D. Bogdanov, C. Breyer, M. Fasihi, D. Bogdanov and C. Breyer, *Sustainability*, 2017, **9**, 306.

29 J. M. Ogden, M. M. Steinbugler and T. G. Kreutz, *J. Power Sources*, 1999, **79**, 143–168.

30 S. Giddey, S. P. S. Badwal, C. Munnings and M. Dolan, *ACS Sustainable Chem. Eng.*, 2017, **5**, 10231–10239.

31 J. Dewar, *Proc. R. Soc. London*, 1898, **63**, 256–258.

32 S. Kamiya, M. Nishimura and E. Harada, *Phys. Procedia*, 2015, **67**, 11–19.

33 B. H. R. Suryanto, H.-L. Du, D. Wang, J. Chen, A. N. Simonov and D. R. MacFarlane, *Nat. Catal.*, 2019, 1.

34 C. H. Christensen, T. Johannessen, R. Z. Sørensen and J. K. Nørskov, *Catal. Today*, 2006, **111**, 140–144.

35 J. Gosens, F. Hedenus and B. A. Sandén, *Energy*, 2017, **131**, 267–278.

36 S. Carley, E. Baldwin, L. M. MacLean and J. N. Brass, *Environ. Resour. Econ.*, 2017, **68**, 397–440.

37 P. J. Loftus, A. M. Cohen, J. C. S. Long and J. D. Jenkins, *Wiley Interdiscip. Rev. Clim. Change*, 2015, **6**, 93–112.

38 M. Suškevičs, S. Eiter, S. Martinat, D. Stober, E. Vollmer, C. L. de Boer and M. Buchecker, *Land Use Policy*, 2019, **81**, 311–323.

39 S. R. Leather and D. J. L. Quicke, *Environmentalist*, 2009, **30**, 1–2.

40 U. Liebe, A. Bartczak and J. Meyerhoff, *Energy Policy*, 2017, **107**, 300–308.

41 K. Jenkins, D. McCauley, R. Heffron, H. Stephan and R. Rehner, *Energy Res. Soc. Sci.*, 2016, **11**, 174–182.

42 J. Rand and B. Hoen, *Energy Res. Soc. Sci.*, 2017, **29**, 135–148.

43 C. Brannstrom, A. Gorayeb, J. de Sousa Mendes, C. Loureiro, A. J. de, A. Meireles, E. V. da Silva, A. L. R. de Freitas and R. F. de Oliveira, *Renewable Sustainable Energy Rev.*, 2017, **67**, 62–71.

44 M. Z. Jacobson, M. A. Delucchi, Z. A. F. Bauer, S. C. Goodman, W. E. Chapman, M. A. Cameron, C. Bozonnat, L. Chobadi, H. A. Clonts, P. Enevoldsen, J. R. Erwin, S. N. Fobi, O. K. Goldstrom, E. M. Hennessy, J. Liu, J. Lo, C. B. Meyer, S. B. Morris, K. R. Moy, P. L. O'Neill, I. Petkov, S. Redfern, R. Schucker, M. A. Sontag, J. Wang, E. Weiner and A. S. Yachanin, *Joule*, 2017, **1**, 108–121.

45 P. Meyfroidt, R. Roy Chowdhury, A. de Bremond, E. C. Ellis, K.-H. Erb, T. Filatova, R. D. Garrett, J. M. Grove, A. Heinimann, T. Kuemmerle, C. A. Kull, E. F. Lambin, Y. Landon, Y. le Polain de Waroux, P. Messerli, D. Müller, J. Ø. Nielsen, G. D. Peterson, V. Rodriguez García, M. Schlüter, B. L. Turner and P. H. Verburg, *Glob. Environ. Change*, 2018, **53**, 52–67.

46 A. W. Schäfer, A. D. Evans, T. G. Reynolds and L. Dray, *Nat. Clim. Change*, 2016, **6**, 412–417.

47 S. J. Davis, N. S. Lewis, M. Shaner, S. Aggarwal, D. Arent, I. L. Azevedo, S. M. Benson, T. Bradley, J. Brouwer, Y.-M. Chiang, C. T. M. Clack, A. Cohen, S. Doig, J. Edmonds, P. Fennell, C. B. Field, B. Hannegan, B.-M. Hodge, M. I. Hoffert, E. Ingersoll, P. Jaramillo, K. S. Lackner, K. J. Mach, M. Mastrandrea, J. Ogden, P. F. Peterson, D. L. Sanchez, D. Sperling, J. Stagner, J. E. Trancik, C.-J. Yang and K. Caldeira, *Science*, 2018, **360**, eaas9793.

48 S. Brynolf, E. Fridell and K. Andersson, *J. Cleaner Prod.*, 2014, **74**, 86–95.

49 T. A. Napp, A. Gambhir, T. P. Hills, N. Florin and P. S. Fennell, *Renewable Sustainable Energy Rev.*, 2014, **30**, 616–640.

50 M. Zeyringer, J. Price, B. Fais, P.-H. Li and E. Sharp, *Nat. Energy*, 2018, **3**, 395–403.

51 A. E. MacDonald, C. T. M. Clack, A. Alexander, A. Dunbar, J. Wilczak and Y. Xie, *Nat. Clim. Change*, 2016, **6**, 526–531.

52 J. Schmidt, R. Cancella and A. O. Pereira Jr., *Renewable Energy*, 2016, **85**, 137–147.

53 B. V. Mathiesen, H. Lund, D. Connolly, H. Wenzel, P. A. Østergaard, B. Möller, S. Nielsen, I. Ridjan, P. Karnøe, K. Sperling and F. K. Hvelplund, *Appl. Energy*, 2015, **145**, 139–154.

54 B. V. Mathiesen and H. Lund, *IET Renew. Power Gener.*, 2009, **3**, 190–204.

55 F. Ueckerdt, L. Hirth, G. Luderer and O. Edenhofer, *Energy*, 2013, **63**, 61–75.

56 Y. Scholz, H. C. Gils and R. C. Pietzcker, *Energy Econ.*, 2017, **64**, 568–582.

57 R. A. Rodriguez, S. Becker and M. Greiner, *Energy*, 2015, **83**, 658–668.

58 L. Reichenberg, F. Hedenus, M. Odenberger and F. Johnsson, *Energy*, 2018, **152**, 914–924.

59 N. A. Sepulveda, J. D. Jenkins, F. J. de Sisternes and R. K. Lester, *Joule*, 2018, **2**, 2403–2420.

60 World Bank Group, Global Solar Atlas, http://globalsolaratlas.info.

61 T. S. Schmidt, *Nat. Clim. Change*, 2014, **4**, 237–239.

62 IRENA, Renewable Energy Auctions: Analysing 2016, http://www.irena.org/publications/2017/Jun/Renewable-Energy-Auctions-Analysing-2016, accessed September 14, 2018.

63 A. Gulagi, D. Bogdanov, M. Fasihi and C. Breyer, *Sustainability*, 2017, **9**, 233.

64 K. C. Seto, S. J. Davis, R. B. Mitchell, E. C. Stokes, G. Unruh and D. Ürge-Vorsatz, *Annu. Rev. Environ. Resour.*, 2016, **41**, 425–452.

65 P. Erickson, S. Kartha, M. Lazarus and K. Tempest, *Environ. Res. Lett.*, 2015, **10**, 084023.

66 N. Bauer, C. McGlade, J. Hilaire and P. Ekins, *Nat. Clim. Change*, 2018, **8**, 130–134.

67 C. McGlade and P. Ekins, *Nature*, 2015, **517**, 187–190.

68 J. Schmidt, M. Schönhart, M. Biberacher, T. Guggenberger, S. Hausl, G. Kalt, S. Leduc, I. Schardinger and E. Schmid, *Energy Policy*, 2012, **47**, 211–221.

69 M. Pichler, *Dev. Change*, 2015, **46**, 508–533.

70 S. Proskurina, M. Junginger, J. Heinimö, B. Tekinel and E. Vakkilainen, *Biofuels, Bioprod. Biorefin.*, 2019, **13**, 371–387.