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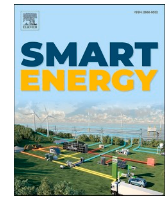

How replacing fossil fuels with electrofuels could influence the demand for renewable energy and land area

Anders Winther Rennuit-Mortensen [a,1], Kasper Dalgas Rasmussen [a,2], Maria Grahn [b,*]

[a] *SDU Life Cycle Engineering, Department of Chemical Engineering, Biotechnology and Environmental Technology, University of Southern Denmark, Campusvej 55, 5230, Odense M, Denmark*

[b] *Department of Mechanics and Maritime Sciences, Maritime Environmental Sciences, Chalmers University of Technology, 412 96, Gothenburg, Sweden*

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ABSTRACT

During recent years, electrofuels (fuels from electricity, water, and carbon) have gained increased interest as substitute for fossil fuels in all energy and chemical sectors. The feasibility of electrofuels has been assessed from a range of aspects but no study has assessed the land area needed if scaling up the production based on renewables. The amount of land on Earth is limited and the competition for land, in a long-term perspective, imposes a risk of, e.g., increased food prices and biodiversity losses. The aim of this paper is to assess how much land area it would require if all fossil fuels were substituted by electrofuels ('All electrofuel'-scenario) and compare this with the area needed if all fossil fuels were substituted by bioenergy ('All biomass'-scenario) or by electricity ('All electric'-scenario). Each scenario represents extreme cases towards fully renewable energy systems to outline the theoretical area needed. Main conclusions are (1) the electricity demand, if substituting all fossil fuels with electrofuels, is huge (1540 EJ) but technically obtainable, demanding 1.1% of the Earth's surface, for solar panels, in the most optimistic case, and (2) the sustainable technical potential for biomass cannot alone substitute all fossil fuels, unless radical energy demand reductions.

1. Introduction

In 2015, the world agreed in the Paris Agreement to limit global warming to well below 2 °C compared to the pre-industrial levels and to pursue efforts to limit the global warming to 1.5 °C [1]. The extraction and burning of fossil fuels for energy purposes, makes up the largest contribution to the global warming through its emittance of greenhouse gas emissions [2]. To limit these emissions, two main approaches can be taken to develop a low-carbon energy system. The first one is directly avoiding CO_2-emissions by using renewable energy sources. The other approach is to reduce CO_2-emissions by focusing on energy savings or utilize carbon capture and storage (CCS) of CO_2. This paper will focus on a global fully renewable energy system where no fossil fuels are used in 2060, thus following the first approach.

Electrofuels (also denoted, e.g., e-fuels and power-to-fuels) are gaseous or liquid hydrogen-containing fuels produced from electricity, water, and in many cases carbon which is used to form hydrocarbons [3–6]. The carbon can be supplied from CO_2 point sources such as biomass incineration, biogas, or fermentation. The carbon can also be supplied from direct air capture (DAC). Fuels such as methane, gasoline, diesel, and jet fuel can be produced as electrofuels, thus fossil oil and gas-based fuels could be substituted by electrofuels. The interest for substituting fossil fuels with electrofuels has increased during recent years, see e.g., Refs. [4,5]. Advantages include the possibility for many hydrocarbon electrofuels being used in existing vehicles and may not require significant investments in new distribution and fueling infrastructure. Long-distance transport modes, especially aviation and deep-sea shipping where electrification opportunities are limited, may find electrofuels of special interest since liquid fuels generally have high energy density and thus more energy can be carried onboard. Electrofuels could also contribute to balancing intermittent electricity production by providing a use for excess or very low-cost electricity [7]. Electrofuels may also allow for increased biofuel production by using the associated excess CO_2 [8] and may generate marketable by-products such as high-purity oxygen and heat [5]. However, production costs are currently relatively high, and the combined efficiency of energy

* Corresponding author.
E-mail address: maria.grahn@chalmers.se (M. Grahn).
[1] Present address: Systems perspective, Energinet, Tonne Kjærsvej 65, 7000 Fredericia, Denmark.
[2] Present address: Department of Quality and Continuous Improvement, Ib Andresen Industri, Industrivej 12, 5550 Langeskov, Denmark.

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conversion and utilization is a challenge compared to options that use electricity directly, see e.g., Refs. [4,5,9–11]. The large quantities of renewable electricity needed when scaling up the electrofuel production [12,13], will demand large land areas if supplied by solar and wind farms.

The amount of land on Earth is limited and the competition for land, in a long-term perspective, imposes a risk of increased food prices, biodiversity issues with a need for increased protection of sensitive eco systems. Different production pathways for alternative fuels claim different types and quantities of land. Therefore, comparing land efficiency for energy purposes (the energy yield per hectare of land) is an important question that adds knowledge to the complex issue of choosing alternative fuel options that have the potential to be scaled up. Currently, of the 13 billion hectare (Gha) of global ice-free land area, approximately 1% is infrastructure, 22% is used for forestry, 12% for crop production, 37% is pasture-land, and 28% is ecosystems with minimal human use [14].

According to a Scopus search on electrofuels, using the following search string,

TITLE-ABS-KEY ((electrofuel OR efuel* OR "e-fuel*" OR "electro-fuel*" OR "e-gas" OR "e-methane" OR "e-methanol" OR "e-gasoline" OR "e-diesel" OR "e-kerosene" OR "e-ammonia" OR "e-liquid" OR "electro-methane" OR "electro-methanol" OR "electro-gasoline" OR "electro-diesel" OR "electro-kerosene" OR "electro-ammonia" OR "electro-liquid*" OR electromethane OR electromethanol OR electrogasoline OR electrodiesel OR electrokerosene OR electroammonia OR electroliquid* AND (carbon OR nitrogen)) OR (powerfuel* OR "power-fuel*" OR ((ptx OR ptl OR ptg OR "power-to-*") AND (methane OR methanol OR gasoline OR diesel OR kerosene OR ammonia OR fuel* OR liquid*)) OR "CO2-fuel*" OR "CO2-derived fuel*" OR "CO2-based fuel*" OR "hydrogen-based synthetic fuel*" OR "hydrogen-based fuel*" AND ("carbon recycling" OR "carbon conversion" OR "carbon capture" OR "carbon capture and utilization" OR "carbon capture and utilisation" OR ccu OR "direct air capture"))),*

over 1300 peer reviewed scientific articles have been published on different aspects of electrofuels but none of them have analyzed the global area demand for large scale production of these fuels. However, one recent paper compares the land area required to meet the energy demand for heavy-duty transport with biofuels or electrofuels in Ireland [15], and one German report has calculated the area demand for electro-jet fuel production for the aviation sector [16], but not for the entire energy system.

The aim of this paper is to assess how much energy and consequently how much land area it would require if all fossil fuels were substituted by electrofuels and compare this with the area needed if all fossil fuels were substituted by bioenergy or by electricity. The three assessed scenarios consist of an 'All electrofuel'-scenario where all fossil fuels are substituted with electrofuels, an 'All biomass'-scenario where all fossil fuels are substituted with biomass, and an 'All electric'-scenario where all fossil fuels are substituted with renewable electricity. Focus is on land area needed for the renewable energy and we have disregarded from the area needed for, e.g., carbon capture and fuel synthesis.

The electricity, for the electrofuels and electrification scenarios, is assumed to be supplied from wind and solar power. We have chosen to focus on wind, solar, and biomass although there are other non-fossil power options. For example, nuclear power is excluded from this analysis since it is not a renewable energy source and hydropower as well as other renewable sources as geothermal, wave etc. remain as they are. To fully explore the extremes, we have chosen to disregard from resource limitations of wind, solar and biomass, although all energy sources have supply potential limitations, where, e.g., the global sustainable technical potential for biomass is estimated to around 100–300 EJ in 2050 [17–19] (read more on biomass limitations in the discussion). The scenarios assumed in this paper, are thus not realistic scenarios, but extreme cases that will help to outline the theoretical land area needed, to help understand the feasibility of each scenario. A medium case has been presented in Section 4.4 to facilitate land area comparisons.

This paper consists of two parts. First, a brief overview of fossil fuels used today and renewable alternatives for substituting the fossil fuels. Special attention has been given to processes using coal, since coal is harder or impossible to make from renewable electricity and carbon dioxide in contrast to methane and liquid fuels.

Second, the three global fully renewable energy scenarios are developed using data for 2017 on total primary energy supply (TPES) from the World Energy Balances from the International Energy Agency (IEA) [20] and projections for 2060 based on their Energy Technology Perspectives [21]. Energy sources are changed according to each scenario characteristic, i.e., electrofuels, biofuels, and electrification. From the resulting amount of energy, area demands are calculated based on reviews of area energy densities for wind, solar, and biomass. Results can add perspectives to the larger question if there are any showstoppers connected to an increased use of electrofuels.

2. Current fossil fuel use and the renewable alternatives

Fossil fuels are currently used to a wide extent and for a lot of purposes. This section will give an overview of the major uses and some of the possible renewable alternatives.

2.1. Coal use

In 2017, TPES of coal was around 160 EJ [20] with the major uses being:

- >70 EJ for electricity production
- >25 EJ for combined heat and electricity production
- ≈25 EJ for iron and steel production
- ≈10 EJ for high temperature process heat, i.e., to produce glass, ceramic, cement, etc.

Coal for producing electricity and heat could potentially be fully replaced by renewable energy sources. Wind and solar power deliver a fluctuating electricity supply and by combining this with flexible production from, e.g., gas turbines running on electro-methane, hydropower, or batteries the production can fulfill the demand. Heat can come from electric heat pumps, solar thermal energy or from burning electro-methane. Replacing coal for heat and electricity production is mainly a question of economical prioritization.

For the two other major uses of coal, i.e., high temperature process heat, and iron and steel production it is possible to replace coal, as can be seen in the following examples.

In cement production the kiln is heated to around 1400-1500 °C [22] by a long flame which can also be produced from, e.g., methane or hydrogen, both can be produced as electrofuels. Another option is to use electricity which is being assessed in the CemZero project [22]. There is no electric pilot plant yet, but a further in-depth study is planned. Displacing fossil fuels in cement production will not remove all CO_2-emissions from the production as about two-thirds of the emissions today are generated from decomposing limestone [23]. CCS is therefore needed if cement production should become CO_2-neutral, and all fossil fuels should be technically avoidable in cement production.

Almost all iron-ore extraction (98%) are used for the production of steel [24]. The Swedish HYBRIT project aims at producing fossil-free steel [25]. In Sweden today, around 5150 kWh of coal, 81 kWh of oil, and 235 kWh of electricity is used to produce 1 ton of crude steel which results in 1600 kg of CO_2-emissions [26]. For the HYBRIT setup these numbers are 560 kWh of biomass, 42 kWh of coal and 3488 kWh of electricity whereof most of the electricity goes to producing hydrogen. The resulting CO_2-emission of the HYBRIT process is 25 kg whereof 20 kg comes from lime making and 5 kg comes from coal [26]. Lime and coal are used to remove impurities and to adjust the final properties of the steel. Thus, it seems not possible to avoid coal completely in steel production, but it can be significantly reduced, and the remaining share can be small.

Going from a mainly coal-based to a mainly electricity-based steel production requires a transition from traditional blast furnaces to direct reduction of iron (DRI) with hydrogen from electrolysis followed by an electric arc furnace. In blast furnaces coal could to some extent be replaced by biomass, charcoal from biomass pyrolysis or methane, e.g., electro-methane [27,28]. Another option is to substitute some of the coal with hydrogen, which the industrial engineering and steel company ThyssenKrupp is testing, before eventually converting to the DRI route and electric arc furnaces [29]. Other options are also being investigated [30,31].

The remaining uses of coal, not mentioned above, are all small and has been judged technically possible to replace with electricity, hydrogen, electro-methane or other electrofuels, except when coal is used for non-energy purposes and is part of the final product, e.g., some chemicals, silicon carbide and carbon anodes [32,33]. In this study we have chosen to exclude the small share of coal use not possible to replace.

2.2. Oil use

For crude oil an oil products TPES was around 190 EJ [20] in 2017 with the major uses being:

- >80 EJ for road transportation
- >20 EJ for chemicals and petrochemicals, including feedstocks
- ≈10 EJ for world marine bunkers
- ≈10 EJ for world aviation bunkers
- ≈10 EJ for electricity production
- ≈10 EJ energy industry own use
- ≈10 EJ for residential purposes

It is technically possible to produce almost all oil products as electrofuels. At historical oil prices, electrofuels are more expensive than fossil oil-based fuels [5], however in parity with hydrogen in fuel cells and battery electric propulsion options depending on transport mode, distance and technical feasibility assumptions [11,34]. As prices for batteries fall, and charging infrastructure improve, battery electric propulsion may be the most attractive option for light-duty vehicles. Moreover, electric solutions in cities have advantages as reduced NOx, soot, and noise, indicating benefits for electric vehicles. There are, however, several challenges for electrifying long-distance transport (especially ships and aircraft), where electrofuels may complement biofuels as renewable liquid options having high energy density, which is beneficial for the size of energy storage onboard.

For the chemicals and petrochemicals, the feedstock is hydrocarbons (currently mainly oil). Oil can in these applications be replaced by electrofuels. Oil used for other purposes has been judged to be possible to substitute with electrofuels, biofuels, or electricity.

2.3. Gas use

For natural gas TPES was around 130 EJ [20] in 2017 with the major uses being:

- >35 EJ for electricity production
- ≈20 EJ for residential purposes
- ≈15 EJ for chemicals and petrochemicals, including feedstocks
- ≈15 EJ for combined heat and electricity production
- ≈10 EJ energy industry own use
- ≈10 EJ for commercial and public services

It is technically possible to produce methane as an electrofuel and since natural gas is basically methane, it is technically possible for most uses to replace natural gas with electro-methane. Therefore, it is not necessary to replace natural gas with, e.g., electricity or hydrogen, but it could be likely to happen if the price of methane increases. Electricity production can be made by wind or solar power and heat by solar thermal power or heat pumps. Methane for residential, commercial, and public purposes, e.g., space heating and for cooking, should be technically replaceable with electricity.

3. Method and materials

3.1. Renewable energy scenarios

The assessments focus on how much energy and consequently how much land area the three different global renewable energy extreme scenarios would require. The scenarios are developed using energy supply data for 2017 from the World Energy Balances by International Energy Agency (IEA) [20] and the projections for 2060 are based on their Energy Technology Perspectives 2017 [21]. The energy supply projections used for this paper are based on IEA's Reference Technology Scenario (RTS), which represents countries' commitments to limit their emissions and improving energy efficiency. The reason for choosing scenarios based on 2017 is that these scenarios were available, and since focusing on 2060, where extreme scenarios are studied, we believe exact starting year for the scenarios is of minor importance. Following the RTS will, according to IEA, lead to a temperature increase of 2.7 °C by 2100, but by substituting fossil fuels with renewable energy sources, as in this paper, the temperature increase will be lower. It is outside the scope of this paper to assess the temperature.

All data below is for 2060 to show the largest energy demand projected under the RTS. In the RTS, the coal supply is increased from around 160 EJ in 2017 to around 165 EJ in 2060, oil supply is increased from around 190 EJ in 2017 to around 210 EJ in 2060, and gas supply is increased from around 130 EJ in 2017 to around 190 EJ in 2060. The general projections for 2060 have been divided into subcategories assuming the same subcategories, and corresponding ratio, as presented in the world energy balances for 2017 [20]. The total numbers of subcategories, for each type of energy carrier, are presented in Table 1.

The TPES data for the RTS has been modified to fit the characteristics for each of the three scenarios. The three global renewable energy scenarios considered in this paper are:

1. **All electrofuel.** All fossil fuels and biofuels are substituted by electrofuels. Also, electricity from nuclear is replaced by electricity from electro-methane due to the reasons mentioned in the introduction. Biomass-based heat, electricity and fuels are as well replaced by electrofuels. Electricity from hydropower and other renewables remain.
2. **All biomass.** All fossil fuels are substituted by biofuels, furthermore all other types of electricity production are substituted with biomass-based electricity to explore the extreme of an all-biomass scenario. The effect of not substituting nuclear, hydro, and other renewable power sources by biomass-based electricity is shown in Section 4.4.
3. **All electric.** All fossil fuels, nuclear, and biomass-based fuels, heat, and electricity are substituted by renewable electricity (solar and wind), whereas electricity from hydropower and other renewable power sources remain. A direct electrification, or battery electrification, is assumed in this scenario for all processes although there might be technical challenges for some applications.

3.2. Energy demand

An overview of the modified TPES and substitution assumptions made in this paper for each scenario, type of energy carrier, and subcategory can be found in Table 2. The values are for 2060 and the unit is exajoule (EJ).

The focus of this paper is on electrofuels and the energy and land-area consequences of scaling these up to the extreme described in the

Table 1
Number of subcategories for each type of energy carrier [20].

Energy carrier	Coal	Natural gas	Oil	Biomass	Nuclear	Hydro and other renewables
Total number of subcategories	**34**	**34**	**45**	**30**	**5**	**14**
Number of subcategories in:						
- Heat and electricity prod.	7	7	7	7	5	9
- Industry	20	18	21	15	0	1
- Transport	0	3	8	4	0	0
- Other	4	4	5	4	0	4
- Non-energy use	3	2	4	0	0	0

Based on '*IEA World Energy Balances* [20]. *All rights reserved.' as* modified by Anders Winther Rennuit-Mortensen.

Table 2
Overview of substitution assumptions made in this paper for 2060 [EJ], based on [20,21], for each type of energy carrier, for each of the three global renewable energy scenarios. Most of the values are similar for each scenario apart from where efficiencies differ, see Table 3 and text.

Energy demand [EJ] for each type of energy carrier and subcategory	Coal	Natural gas	Oil	Biomass	Nuclear	Hydro and other renewables
IEA's Reference Technology Scenario (RTS)						
Total	**164**	**192**	**211**	**99**	**57**	**121**
- Heat and electricity prod.	103	78	11	15	57	105
- Industry	52	56	28	22	0.0	0.3
- Transport	0.0	6.5	122	6.2	0.0	0.0
- Other	6.6	40	20	56	0.0	16
- Non-energy use	2.2	12	30	0.0	0.0	0.0
Scenarios:	*Substituted by*	*Substituted by*	*Substituted by*	*Substituted by*	*Substituted by*	*Substituted by*
1: All electrofuel	***Electro-methane***	***Electro-methane***	***Liquid -electrofuel***	***Electro-methane***	***Electro-methane***	***Electricity wind/ solar***
Total	***164***	***192***	***211***	***99***	***57***	***89***
- Heat and electricity prod.	103	78	11	15	57	83
- Industry	52	56	28	22	0.0	0.1
- Transport	0.0	6.5	122	6.2[a]	0.0	0.0
- Other	6.6	40	20	56	0.0	6.4
- Non-energy use	2.2	12	30	0.0	0.0	0.0
2: All biomass	***Biomass***	***Biomass***	***Biomass***	***Biomass***	***Biomass***	***Biomass***
Total	***164***	***192***	***211***	***99***	***57***	***121***
- Heat and electricity prod.	103	78	11	15	57	105
- Industry	52	56	28	22	0.0	0.3
- Transport	0.0	6.5	122	6.2	0.0	0.0
- Other	6.6	40	20	56	0.0	16
- Non-energy use	2.2	12	30	0.0	0.0	0.0
3: All electric	***Electricity wind/ solar***	***Electricity wind/ solar***	***Electricity wind/ solar***	***Electricity wind/ solar***	***Electricity wind/ solar***	***Electricity wind/ solar***
Total	***100***	***149***	***150***	***89***	***19***	***89***
- Heat and electricity prod.	39	35	3.6	4.6	19	83
- Industry	52	56	28	22	0.0	0.1
- Transport	0.0	6.5	67	6.2	0.0	0.0
- Other	6.6	40	20	56	0.0	6.4
- Non-energy use	2.2	12	30	0.0	0.0	0.0

Based on *'IEA World Energy Balances* [20]. *All rights reserved.'* And *'IEA Energy Technology Perspectives* [21]. *All rights reserved.'* As modified by Anders Winther Rennuit-Mortensen.
[a] Substituted by liquid electrofuels (electro-diesel, electro-jetfuel etc).

'All electrofuel'-scenario. The biomass scenario is added as a comparison and not dealt with in detail. This is the reason for why fossil fuels are assumed to be substituted one to one in the biomass scenario, i.e., 1 EJ of biomass is replacing 1 EJ of coal, oil, or gas, which is a simplification since conversion losses are not identical but depend on biomass types, desired products, and conversion pathways. Also, the area energy density for biomass varies a lot and in the area demand calculations both an optimistic (high area energy densities) as well as a less optimistic case for biomass area energy densities are used, which to some extend can cover for these simplifications, read more in Section 3.3.

In the 'All electric'-scenario, electricity is provided directly from wind or solar power, thus there is no fuel and no losses from fuel to electricity. Heat production is replaced by electric heat pumps with a coefficient of performance (COP) of 2.5. The data for heat and electricity production and the efficiencies for each scenario can be found in Table 3. For all other applications, in the 'All electric'-scenario fossil fuels are substituted one to one with electricity, except for oil used in road transport as battery electric vehicles (BEV's) are assumed to use 41% of the energy used in internal combustion engines (ICE) to provide the same mechanical energy. This is based on an ICE efficiency of 30%, an electric motor efficiency of 90%, a battery efficiency of 85%, and 5% losses in the electric distribution grid. Other applications of direct use of electricity might also come with efficiency improvements, but they are not considered as some applications, e.g., aviation will be technically limited in using batteries or direct electrification. For the subcategory *'Other'* for *hydro and other renewables* the numbers are also lower for the 'All electric'-scenario as it has been assumed that heat is demanded and that it can be supplied from a heat pump with a COP of 2.5.

From the modified TPES for each scenario, Tables 2 and it is possible to calculate the total demand for electricity needed to produce electrofuels in the 'All electrofuel'-scenario. The conversion efficiencies of electricity to heat and hydrogen, and hydrogen to methane and liquid electrofuels (electro-diesel, electro-jetfuel etc) are assumed to be:

- Electricity to heat: 250% (η_{heat}) (Electric heat pump with a COP of 2.5 for direct air capture (DAC) of CO_2) [35]

Table 3
Heat and electricity production, efficiencies, and outputs for all scenarios and all types of energy carrier, based on [20,21]. Note that it is mainly the 'All electric'-scenario that differs, due to different efficiency assumptions. The efficiency for 'heat plants' in the 'Hydro and other renewables' is high since primary energy input does not take into account the "ambient" heat from, e.g., geothermal heat.

Energy demand [EJ] and efficiencies for each type of energy carrier, of the subcategory "Heat and electricity prod."	Coal	Natural gas	Oil	Biomass	Nuclear	Hydro and other renewables
IEA's Reference Technology Scenario (RTS)-scenario, *'All electrofuel'*-scenario, and *'All biomass'*-scenario						
Total	***103***	***78***	***11***	***15***	***57***	***105***[a]
Electricity plants	***74***	***54***	***9.4***	***9.2***	***57***	***104***
Efficiency	*38%*[b]	*45%*	*34%*	*25%*	*33%*	*78%*
Electricity output	28	24	3.2	2.3	19	81
CHP plants	***28***	***20***	***0.8***	***4.7***	***0.5***	***1.0***
CHP efficiency	*51%*	*64%*	*59%*	*56%*	*41%*	*49%*
Electricity output	8.9	6.9	0.2	1,5	0.1	0.3
Heat output	5.4	5.9	0.2	1.2	0.1	0.2
Heat plants	***1.0***	***4.0***	***0.5***	***0.9***	**-**	***0.5***
Efficiency	*86%*	*83%*	*79%*	*79%*	-	*719%*[c]
Heat output	0.8	3.3	0.4	0.7	–	3.8
***'All electric'*-scenario**						
Total electricity	***39***	***35***	***3.6***	***4.6***	***19***	***83***
Electricity plants	***28***	***24***	***3.2***	***2.3***	***19***	***81***
Efficiency	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*
Electricity output	28	24	3.2	2.3	19	81
CHP plants	***11***	***9.3***	***0.3***	***2.0***	***0.2***	***0.4***
Efficiency	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*
Electricity output	8.9	6.9	0.2	1.5	0.1	0.3
Efficiency[d]	*250%*	*250%*	*250%*	*250%*	*250%*	*250%*
Heat output	5.4	5.9	0.2	1.2	0.1	0.2
Heat plants	***0.3***	***1.3***	***0.1***	***0.3***	**-**	***0.5***
Efficiency	*250%*	*250%*	*250%*	*250%*	-	*719%*[c]
Heat output	0.8	3.3	0.4	0.7	–	3.8

[a] The 'All electrofuel'-scenario follows the 'All electric'-scenario in this category, i.e. heat pumps assumed for heat generation otherwise generated from other renewables, resulting in 83EJ.

[b] It is assumed that e-methane/biomethane is replacing coal for electricity production. Although efficiencies differ between coal (approx. 38%) and gas powerplants (approx. 45%), modern coal-fired plants are almost as efficient as gas-turbines (both technologies within the range of 45-55% [35]) and as a transparent simplification 1:1 substitution is assumed.

[c] Calculated as Heat output divided by Heat plants, using non-rounded numbers as 3.8355 and 0.5337.

[d] The effect on results by assuming alternative efficiency on heat pumps are discussed in Section 4.4.

- Electricity to hydrogen: 70% (η_{H_2}) [5,35]
- Hydrogen to methane: 80% (η_{CH_4}) [5,35]
- Hydrogen to liquid fuels: 75% ($\eta_{liqfuel}$) [5,35]
- Wind/solar to electricity: 100% (η_{elec})_ [35]

The carbon for producing the electrofuels has been assumed to come from DAC of CO_2 where it is assumed that to capture 1 ton of CO_2 250 kWh of electricity (0.9 EJ/Gt) and 1750 kWh of thermal energy (6.3 EJ/Gt) at 100 °C are needed [36]. The heat is assumed to be delivered by an electric heat pump. It is possible to obtain CO_2 in more energy efficient ways, but DAC has been chosen to represent an infinite source.

As an example of the methodology consider, the 'All electrofuel'-scenario and the approximately 74 EJ of coal used, in the 'RTS'-scenario, for the further subcategory of pure electricity production of approximately 28 EJ of electricity. These 74 EJ of coal are substituted with electro-methane in the 'All electrofuel'-scenario i.e., the efficiency for electro-methane to electricity is simplified to be the same as coal to electricity. To produce 74 EJ of electro-methane, hydrogen should be produced, carbon should be captured, and both components should be reacted into electro-methane. This requires around 145 EJ of electricity as illustrated below, where *eMethane* (EJ) is the amount of electro-methane needed to substitute coal-based electricity, η_{H_2} is the conversion efficiency from electricity to hydrogen, η_{CH_4} is the conversion efficiency of hydrogen to methane, m_{CO2} (Gt) is the mass of CO_2 needed to provide the required carbon, $\beta_{CO_{2electric}}$ (EJ/Gt) is the electric input to DAC, $\beta_{CO_{2heat}}$ (EJ/Gt) is the heat input to DAC, and η_{heat} is the conversion efficiency from electricity to heat:

$$Electricity\ demand = \frac{eMethane}{\eta_{H_2} \cdot \eta_{CH_4}} + m_{CO2} * \beta_{CO_{2electric}} + \frac{m_{CO2} * \beta_{CO_{2heat}}}{\eta_{heat}}$$
$$= \frac{74\ EJ_{electro-methane}}{70\% \cdot 80\%} + 3.7\ Gt_{CO2} \cdot 0.9 \frac{EJ_{electicity}}{Gt_{CO2}} + \frac{3.7\ Gt_{CO2} \cdot 6.3 \frac{EJ_{heat}}{Gt_{CO2}}}{250\%}$$
$$\approx 145\ EJ_{electricity}$$

The mass of CO_2 needed to provide the required carbon is found from the higher heating value of the product i.e., for electro-methane, CH_4 (55.5 MJ/kg) and for liquid electrofuels, $C_{14}H_{30}$ (46.1 MJ/kg) and the following reactions:

$$Electromethane : 4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$$

$$Liquid\ electrofuels : 43\ H_2 + 14\ CO_2 \rightarrow C_{14}H_{30} + 28\ H_2O$$

A similar procedure has been made for all subcategories and all types of energy carriers for each scenario. The area demand is found by multiplying the total electricity or biomass demand for each scenario with the relevant data found in Section 3.3.

3.3. Area demand

The land area demand is based on the following brief reviews, where the highest and lowest values of the intervals for wind, solar, and biomass, respectively, will represent an optimistic and a less optimistic case for the area demand calculations. When assessing area demand it should be noted that high area energy densities are preferable as it gives a low area demand (optimistic case). A high area energy density is, thus, preferable over a low area energy density.

A brief review of 5 Danish (Anholt, Horns Rev 2, Horns Rev 3, Kriegers Flak, Nørrekær Enge II) and 7 British (Hornsea 1, Hornsea 2, London Array, Race Bank, Walney, Walney extension, West of Duddon Sands) wind farms show a range from the highest area energy density of 92 MJ/m^2 to the lowest of 34 MJ/m^2 [37–40]. It should be noted that the area energy density depends on local wind speeds and these numbers may not be representative for the global average. We have therefore chosen to not distinguish between onshore and offshore wind but include both types of wind power plants in one category. Results will be compared to the IEA offshore wind potentials as this potential takes undeveloped sites into account as well.

A brief review of 10 solar power parks (Kamuthi Solar Power Project, Solar Star Projects, Topz Solar Farm/Desert Sunlight Solar Farm, Enel Villanueva PV plant, Longyanxia Dam Solar park, Kurnool Ultra Mega Solar Park, Sweihan Photovoltaic Independent Power Project, Bhadla Solar Park, Tengger Desert Solar Park, and Cestas Solar Park) finds the installed capacity per square kilometer to vary between 29 MW/km^2 to 151 MW/km^2 [41]. This translates to an area energy density between 190 MJ/m^2 to 980 MJ/m^2 at a specific photovoltaic power output of 1800 kWh/kWp, which is relatively high. For a lower specific photovoltaic power output of 800 kWh/kWp, which is relatively low, the energy densities vary between 80 MJ/m^2 and 430 MJ/m^2, refer to Ref. [41] for more details.

A brief review of biomass yields per area found sugarcane to be one of the most area efficient plants with an area energy density of 110 MJ/m^2 [42] under good conditions, representing the extreme optimistic case. Area energy densities of less than 45 MJ/m^2 for sugarcane has also been reported [43] and similar yields have been found for willow [44]. For the less optimistic biomass case, 4 MJ/m^2 has been chosen representing ethanol from corn or biodiesel from rapeseed (RME) [45], where conversion losses are taken into account.

Comparing sugarcane, representing the optimistic case for biomass, with the least dense solar power park above a specific solar power production of around 1050 kWh/kWp would give the same area energy density as sugarcane. Most countries growing sugarcane can have higher specific solar power production than 1050 kWh/kWp which means that solar power always would be more area energy efficient than sugarcane. Sugarcanes might be an area efficient route to obtain ethanol but not necessarily for electricity production, this has, however, not been assessed further in this paper.

4. Results and discussion

Based on the assumptions presented, calculations were made on area demand for each of the three scenarios assuming either optimistic case or less optimistic case and for the 'All electrofuel'-scenario and the 'All electric'-scenario also for cases all wind or all solar.

4.1. Area demand

Fig. 1 shows the area demand in million square kilometers (Mkm^2) to provide energy for a global fully renewable energy system, where results also are compared to known geographical land areas (Europe, Africa and Earth of 9.95, 30.1, and 510 Mkm^2 respectively).

The area demands vary greatly from one scenario to another and between the optimistic and less optimistic cases, from the least area demanding case of 0.6 Mkm^2 in the 'All electric' scenario, solar optimistic case, to the most area demanding scenario of 200 Mkm^2 in the 'All biomass' scenario, less optimistic case.

4.2. Comparing area demand to known geographical areas in more detail

In Table 5, the area demand results are presented as percentage of Earth's land surface and for the case of wind to the percentage of Earth's water surface.

The 'All electric'-scenario requires around 600 EJ of electricity and would in the wind case claim 4.9% and 1.8% of Earth's water surface for the less optimistic and the optimistic case, respectively, or 12% and 4.3% of Earth's land surface for the less optimistic case and the optimistic case, respectively, if assuming onshore wind farms. For the optimistic solar case this number is less than 0.5% of Earth's land surface.

The 'All biomass'-scenario less optimistic case would require more land area for biomass production, in 2060, than what is available on planet Earth. The optimistic biomass case would claim around 5% of Earth's land surface. The major challenge with the 'All biomass'-scenario is that it demands more than 840 EJ of biomass per year and thus, around 3 to more than 8 times as much as the sustainable technical potential for bioenergy.

The scenario demanding the most energy is the 'All electrofuel'-scenario where more than 1500 EJ of electricity is needed to supply the energy demands. For the wind case 13% and 4.6% of Earth's water surface for the less optimistic and the optimistic case, respectively, or 31% and 11% of Earth's land surface for the less optimistic case and the optimistic case, respectively, if assuming onshore wind farms, would be covered with wind turbines. For the solar case 1.1% and 12% of Earth's land surface would be claimed for solar panels, corresponding to 7% and 17% of the Sahara Dessert, (which is 9.2 Mkm^2) for the optimistic and less optimistic cases respectively.

4.3. Implications for energy systems modelers

The extremes identified for the land area needed when producing electrofuels, replacing all fossil fuels, i.e., that 1540 EJ of electrofuels from solar or wind demand 1–12% or 11–31% of Earth's land surface, respectively, corresponding to 86–963 or 34–92 MJ of electrofuels per

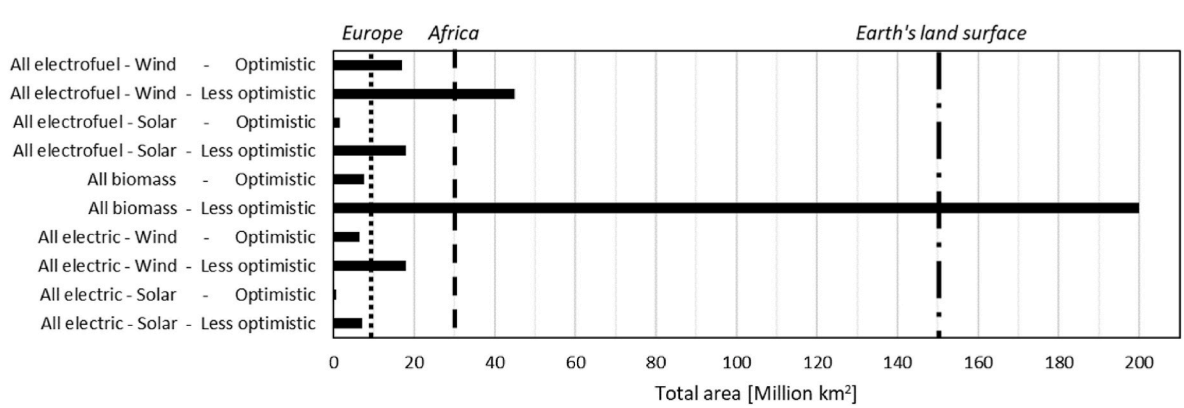

Fig. 1. Results for the three global renewable energy scenarios 'All electrofuel', 'All biomass', and 'All electric', assuming either wind only, solar only, or biomass only for an optimistic case or a less optimistic case. The areas of Europe, Africa, and Earth's land surface have been inserted for comparison.

Table 5
Results for the three global renewable energy scenarios, their electricity and biomass demand, and the area it would take to produce the energy carriers. The area is related to Earth's land surface and for offshore wind related to the area of Earth's water surface. The energy supply of electricity for the 'All electrofuel'-scenario is calculated from Table 2 and the efficiencies presented in text. The energy supply of biomass for the 'All biomass'-scenario is transferred directly from the TPES, Table 2. This is also the case for the 'All electric'-scenario. For both transferred numbers there are minor differences due to slightly different accounting methods.

Energy supply of:	1: All electrofuel		2: All biomass		3: All electric	
Electricity	1540 EJ		0 EJ		594 EJ	
Biomass	0 EJ		843 EJ		0 EJ	
Cases	*Total area:*	*Share of Earth's:*	*Total area:*	*Share of Earth's:*	*Total area:*	*Share of Earth's:*
Wind only	*Million km^2*	*Water surface*[a]			*Million km^2*	*Water surface*[b]
Less optimistic case	45	13%			18	4.9%
Optimistic case	17	4.6%			6.5	1.8%
Solar only	*Million km^2*	*Land surface*			*Million km^2*	*Land surface*
Less optimistic case	18	12%			7.1	4.8%
Optimistic case	1.6	1.1%			0.6	0.4%
Biomass only			*Million km^2*	*Land surface*		
Less optimistic case			200	134%		
Optimistic case			7.7[c]	5.1%		

[a] If comparing to Earth's land surface, the case "Wind only" demands 31% and 11% for the less optimistic case and the optimistic case respectively.
[b] If comparing to Earth's land surface, the case "Wind only" demands 12% and 4.3% for the less optimistic case and the optimistic case respectively.
[c] This result is based on the commercial maximum for sugarcane, which is one of the highest yielding types of biomass and by using the commercial maximum, for the countries with the best conditions, generates a very optimistic case, that can help spanning up the theoretical extreme for land area demand. It should, however, be noted that it is extremely unlikely that these conditions can be found for producing the entire bioenergy demand of 843 EJ. It should also be noted that as a transparent simplification we have assumed biomass to replace fossil fuels 1:1, which gives biomass an advantage since the energy losses are higher for, e.g., biofuels compared to oil-based fuels.

square meter of land producing solar or wind electricity, respectively, highlight the need for energy systems modelers to constrain the maximum supply potentials of electrofuels.

4.4. Is a global fully renewable energy system possible?

A pure biomass-based system, using over 800 EJ of bioenergy, must be judged impossible within the global sustainable technical potential for biomass, estimated to less than 300 EJ, without massive energy savings. Choosing renewable energy supply for a future global renewable energy system is, however, not either/or but both/and, since each type of energy supply has its own advantages and disadvantages, where energy sources not included in this paper also have their merits.

Looking at the 'All electrofuel'-scenario more than 1500 EJ of electricity would have to be provided each year, which is in the same range as a recent estimate by IEA of the global offshore wind potential [46]. Of these estimated 1500 EJ, around 300 EJ is in shallow water (<60 meter) which is suitable for fixed-bottom foundations while 1200 EJ is in deep water (60-2000 meter) which requires floating platforms, Thus, according to Ref. [46] it seems technically possible to base an 'All electrofuel'-scenario on offshore wind farms, but it would require the entire estimated offshore potential to be harvested.

4.5. Effect of alternative input data

In this study, a COP of 250% for heat pumps are assumed, when calculating the total electricity demand in the 'All electric'-scenario, resulting in a total energy demand of 594 EJ. It should be noted that for low temperature heat, e.g., for households, the COP could be 300% or higher. For industrial high temperature heat the COP is lower. If assuming a COP of 150%, the total electricity demand for the 'All electric'-scenario will increase by 5.7 EJ, and if assuming 350% it will decrease by 3.2 EJ. In this study, assessing the big picture, the differences between 591 and 597, for COP 350% and 150% respectively, will not alter the conclusions.

In the definition of 'All biomass'-scenario it is assumed that all types of electricity are substituted with biomass-based electricity. If not substituting nuclear, hydro, and other renewable power sources by biomass-based electricity the demand for bioenergy is lowered to 665 EJ/yr (instead of 843 EJ/yr) and land area to 6.2–163 Mkm^2 (instead of 7.7–200 Mkm^2). The upper extreme still surpassing the world's total land area (109%).

The total area for the 'All biomass'-scenario differ a lot between the extremes assessed. As a medium case, we assume a global average yield of 20 MJ/km^2 (10 dry ton biomass per hectare and 20 GJ per ton dry biomass), which results in an area demand of 42 Mkm^2. As a medium case for wind, we assume a wind area energy density of 65 MJ/m^2 which results in a land area demand of 9 Mkm^2 and 24 Mkm^2 for the 'All electric'-scenario and 'All electrofuel'-scenario, respectively. In this rough medium comparison, it is shown that an 'All biomass'-scenario demands 4.7 and 1.8 times more land area compared to the 'All electric'-scenario and 'All electrofuel'-scenario, respectively.

4.6. Synergies across sectors and strategies for reduced energy demand

There are multiple ways of reducing the demand for energy that have not been assessed in this study. Energy demand reductions could, e.g., be achieved through smart energy systems design [47], process integration [48], synergies across sectors, behavior changes, smart use of advanced digital tools as machine learning, internet of things, and much more.

One example of possible energy reduction when producing electrofuels is the special case in which externally provided hydrogen reacts with surplus CO or CO_2 produced within a biofuel production process (e.g., biomass gasification reactor or anaerobic digestion) giving products called bio-electrofuels [5]. Another example is to utilize more concentrated CO_2 sources from industrial combustion processes, instead of DAC (electricity for DAC is 135 EJ, around 8.8% of the electricity in the 'All electrofuel'-scenario). Another option is to utilize the excess heat from the synthesis of electrofuels. DAC needs heat at around 100 °C, which is lower than the reactor temperature for many synthesis routes.

Synergies between the electricity sector and agriculture/food sector can be expected, since the areas between the wind turbines are possible to use, e.g., for fishing and for harvesting bioenergy on water surface (offshore) as well as for agriculture and livestock (onshore). The land area needed for the 'All biomass'-scenario could as well be used in a multifunctional way, see e.g., Ref. [49]. Also, the area needed for solar panels do not necessarily block the surface from being used for other purposes if, e.g., installed on top of buildings, parking spaces, or similar.

Other examples of synergies across sectors and energy demand reduction strategies can be found in the literature, where for example, Kany et al. [50] lists a range of strategies for reducing the energy demand in the transport sector including electrification and modal shift measures to lower growth in transport demand. Johannsen et al. [51] present strategies for achieving 100% renewable energy in industry before 2050, where energy efficiency improvements are essential. Mathiesen et al. [52] finds that the heating sector can reduce its demand for energy, as well as its consumption of biomass, while still enabling a 100% renewable energy system, and in Mathiesen et al. [53] it was shown that smart energy systems can more than half the energy demand and potentially pave the way to a bioenergy-free 100% renewable energy and transport system.

In summary, there are multiple feedback mechanisms in an energy system affecting the energy demand, and in addition, energy demand is expected to be price-elastic (lowered if more costly technology options enter the market). These effects are also judged beyond the scope of this study.

4.7. Comparing our results to other studies

Schmidt et al. [16] found that the land area needed for PtL fuels appears to be lower than the land requirements for biofuels, which is a result also seen in this study. A similar result is also seen in Gray et al. [15] where a factor of 3, 4 and 10 more land is needed for the production of imported palm oil HVO, grass biomethane, and rapeseed oil biodiesel, respectively, compared to electrofuels production. Lai et al. [54], however, show higher demand for land for two electrofuel production pathways (using either alkaline or PEM electrolysis) compared to two biogenic pathways that are based on forest residues or black liquor, given that both these biomass based resources are judged as waste and therefore not assumed to require any additional land.

4.8. An extreme scenario for aviation

This is an exercise, as an example of what electricity demand would be needed for one single energy sector, i.e., the aviation sector, in case fueled by electrofuels only. In this extreme scenario we assume that 10 billion people by 2050 [55] will fly 20,000 km a year, which is equivalent to one return-trip from New York to Beijing. This is an extreme assumption since the global average air travel per person today is less than 1000 km per year, where 6100 billion air passenger kilometers were travelled [56] divided on a global population of 7.2 billion people [57] for 2014, as a representative year before the Covid pandemic. In this extreme case we further assume all aircraft being propelled by electrofuels, which would require between 367 and 550 EJ of electricity per year, for the fuel production, depending on the aircraft efficiency, see Table 6 for assumptions and results.

The 'high efficiency' scenario requires more energy than the total amount of coal and oil used in 2017, and the 'low efficiency' scenario demands as much energy as the entire 2060 projections for all fossil fuels under the IEA RTS projection. In terms of offshore wind power, between 24% and 37% of the technical potential would have to be used to make aviation fuels. Results thus show that the demand for electricity is high, also when studying one energy sector only, however in an extreme scenario assuming a radically increased demand for aviation fuel in future.

5. Conclusions

By analyzing extreme cases we have found a theoretical solution space on demand for land area needed to substitute fossil fuels with renewable options focusing on electrofuels, and thereby added perspectives to the larger question if there are any showstoppers connected to an increased use of electrofuels. We have found that it is technically possible, from a land area perspective, to substitute all fossil fuels with electrofuels. The amount of electricity needed, is huge but technically obtainable, demanding 1–31% of Earth's land surface, when spanning up the solution space for the most and least optimistic cases of solar and wind (onshore) power production.

The most area efficient type of energy supply is solar power and the least area efficient is certain types of biomass. Results show that the sustainable technical potential for biomass cannot alone be a global solution for providing renewable energy for the global energy systems unless radical energy demand reductions are implemented. Aiming for only one source of energy is though not advisable as all energy sources have their advantages and disadvantages, e.g., wind turbines can be placed offshore, or crops can be grown in between the towers if they are placed on land. Also, solar and bioenergy solutions could be made with multifunctional purposes.

Since the more efficient we can use the energy we harvest, and the less of it we need, the less land area would be required. This study shows that direct electrification, e.g., for road transport reduces the energy demand as well as the land area needed. Regardless of which combination of renewable energy technologies chosen, the consequences of covering large land areas with energy harvesting equipment or crops could be severe and it is therefore important to ensure high area energy densities when scaling up the technologies.

Credit author statement

Anders Winther Rennuit-Mortensen: Conceptualization, Methodology, Formal analysis, Investigation, Writing – Original Draft, Visualization.

Kasper Dalgas Rasmussen: Conceptualization, Methodology, Writing – Review & Editing.

Maria Grahn: Conceptualization, Methodology, Writing – Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 6
Results and assumptions for 10 billion people flying 20,000 km each year, for three cases of aircraft efficiencies (high, medium and low engine efficiency).

Scenarios of aircraft efficiency:	High	Medium	Low	Unit	Ref.
Distance	20,000			km/year	
Aircraft efficiency	0.022	0.025	0.033	liter/seat/kilometer	[58,59]
Fuel per seat	440	500	660	liter/seat	
Energy density of jet fuel	35			MJ/l	
Fuel per seat	15.4	17.5	23.1	GJ/seat	
Passenger load factor	80%			*Range 70%-90%*	[60]
Fuel per passenger	19.25	21.88	28.88	GJ/passenger	
Number of passengers	10			billion	
Results demand for electrofuels	193	219	289	EJ/year	
Efficiency electricity to fuel	53%				
Results demand for electricity	367	417	550	EJ/year	

Data availability

Data will be made available on request.

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