Land and water requirements for the supply of renewable heating and transport energy using anaerobic digestion and water electrolysis. A case study for the UK.

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Abstract

This paper considers nine scenarios for the supply of all the required energy for domestic heating and road transport in the UK from renewable resources and compares their land and water requirements. The scenarios use hydrogen and/or methane as main energy vectors, with anaerobic digestion (AD) of organic waste and energy crops, water electrolysis (WE) and electricity from solar PV panels. The land requirements of WE-based scenarios are much lower than for energy crops. If WE only is used, the land requirement is 1.52 Mha (6 % of the total UK land), which can be decreased by 30-34 % (1.00-1.07 Mha) if WE is used with AD of organic waste. The lowest land requirement (0.73 Mha) is obtained with electric vehicles for transport and WE and AD of organic waste for heating. For most scenarios, the direct water requirements are in the range 40-126 Mt/year (1-4 % of the drinking water supply in the UK). This study indicates that it is possible to supply all the required energy for domestic heating and road transport in the UK from renewable resources, in particular solar PV panels and organic waste, with a moderate impact on land and water use.

Keywords: heating, transport energy, hydrogen, anaerobic digestion, organic waste.

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Nomenclature

Name	Definition	Units
AD	Anaerobic digestion	
A_M	Land area required for miscanthus growth	ha
$A_{PV,tot}$	Total land area required for solar panels	ha
A_{tot}	Total land area required	ha
$CH_{4,t}$	CH_4 required for transport	kg/year
$CH_{4,h}$	CH_4 required for domestic heating	kg/year
$CH_{4,ph}$	CH_4 required for process heating	kg/year
$CH_{4,ADM}$	CH_4 produced from AD of miscanthus, single stage	kg/year
$CH_{4,ADMss}$	CH_4 produced from AD of miscanthus, second stage	kg/year
$CH_{4,ADW}$	CH_4 produced from AD of waste, single stage	kg/year
$CH_{4,ADWss}$	CH_4 produced from AD of waste, second stage	kg/year
$CH_{4,tot}$	Total CH_4 required	kg/year
CHP	Combined heat and power	
DM	Dry matter	
$E_{el/H2}$	Electrical energy per unit hydrogen	J/kg
$E_{el,AD}$	Electrical energy for AD	J/year
$E_{el,ADM/CH4}$	Electrical energy for AD of miscanthus, single stage, per unit CH_4	J/kg
$E_{el,ADMfs/H2}$	Electrical energy for AD of miscanthus, first stage, per unit H_2	J/kg
$E_{el,ADMss/H2}$	Electrical energy for AD of miscanthus, second stage, per unit H_2	J/kg
$E_{el,ADW/CH4}$	Electrical energy for AD of waste, single stage, per unit CH_4	J/kg
$E_{el,ADWfs/H2}$	Electrical energy for AD of waste, first stage, per unit H_2	J/kg
$E_{el,ADWss/CH4}$	Electrical energy for AD of waste, second stage, per unit CH4	J/kg
$E_{el,ADWss/H2}$	Electrical energy for AD of waste, second stage, per unit H_2	J/kg
$E_{el,CH4}$	Electrical energy for CH_4	J/year
$E_{el,CH4/CH4}$	Electrical energy for CH_4 per unit CH_4	J/kg
$E_{el,CH4comp/CH4}$	Electrical energy for CH_4 compression to 200 atm, per unit CH_4	J/kg
$E_{el,CH4M/CH4}$	Electrical energy for CH_4 from miscanthus, per unit CH_4	J/kg
$E_{el,CH4W/CH4}$	Electrical energy for CH_4 from waste, per unit CH_4	J/kg
$E_{el,CO2}$	Electrical energy for CO_2 removal	J/year
$E_{el,CO2/CH4}$	Electrical energy for CO_2 removal, per unit CH_4	J/kg
$E_{el,CO2/H2}$	Electrical energy for CO_2 removal, per unit H_2	J/kg
$E_{el,H2comp}$	Electrical energy for H_2 compression to 700 atm	J/year
$E_{el,H2comp/H2}$	Electrical energy for H_2 compression to 700 atm, per unit H_2	J/kg
$E_{el,Mfs/H2}$	Electrical energy for H_2 from miscanthus, first stage, per unit H_2	J/kg
$E_{el,Mgrowth/CH4}$	Electrical energy for miscanthus growth, per unit CH_4	J/kg
$E_{el,Mgrowth/H2}$	Electrical energy for miscanthus growth, per unit H_2	J/kg
$E_{el,Mss/H2}$	Electrical energy for H_2 from miscanthus, second stage, per unit H_2	J/kg
$E_{el,SMR/H2}$	Electrical energy for SMR, per unit H_2	J/kg
$E_{el,tot}$	Total electrical energy required	J/year
$E_{el,WE}$	Electrical energy for WE	J/year
$E_{el,WE/H2}$	Electrical energy for WE, per unit H_2	J/kg
$E_{el,Wfs/H2}$	Electrical energy for H_2 from waste, first stage, per unit H_2	J/kg
$E_{el,Wss/H2}$	Electrical energy for H_2 from waste, second stage, per unit H_2	J/kg
$E_{h,ADM/CH4}$	Heating energy for AD of miscanthus, single stage, per unit CH_4	J/kg
$E_{h,ADMfs/H2}$	Heating energy for AD of miscanthus, first stage, per unit H_2	J/kg
$E_{h,ADMss/H2}$	Heating energy for AD of miscanthus, second stage, per unit H_2	J/kg
$E_{h,ADW/CH4}$	Heating energy for AD of waste, single stage, per unit CH_4	J/kg
$E_{h,ADWfs/H2}$	Heating energy for AD of waste first stage, per unit H_2	J/kg
$E_{h,ADWss/CH4}$	Heating energy for AD of waste second stage, per unit CH_4	J/kg
$E_{h,ADWss/H2}$	Heating energy for AD of waste, second stage, per unit H_2	J/kg
$E_{h,CO2/CH4}$	Heating energy for CO_2 removal per unit CH_4	J/kg
$E_{h,CO2/H2}$	Heating energy for CO_2 removal per unit H_2	J/kg

Name	Definition	Units
$E_{h,d}$	Domestic heating energy required	J/year
$E_{h,Mgrowth/CH4}$	Heating energy for miscanthus growth per unit CH_4	J/kg
$E_{h,Mgrowth/H2}$	Heating energy for miscanthus growth per unit H_2	J/kg
$E_{h,ph}$	Process heating energy	J/year
$E_{h,ph/CH4}$	Process heating energy for CH_4, per unit CH_4	J/kg
$E_{h,ph/H2}$	Process heating energy per unit H_2	J/kg
$E_{h,phM/CH4}$	Process heating energy for CH_4 from miscanthus, single stage, per unit CH_4	J/kg
$E_{h,phMfs/H2}$	Process heating energy for H_2 from miscanthus first stage, per unit H_2	J/kg
$E_{h,phMss/H2}$	Process heating energy for H_2 from miscanthus second stage, per unit H_2	J/kg
$E_{h,phW/CH4}$	Process heating energy for CH_4 from waste, single stage, per unit CH_4	J/kg
$E_{h,phWfs/H2}$	Process heating energy for H_2 from waste, first stage, per unit H_2	J/kg
$E_{h,phWss/H2}$	Process heating energy for H_2 from waste, second stage, per unit H_2	J/kg
$E_{h,SMR/H2}$	Heating energy for SMR per unit H_2	J/kg
E_{PV}	Electricity from solar PV per unit area	J/year
E_{tot}	Total energy required	J/year
$H_{2,ADMfs}$	H_2 from AD of miscanthus first stage	kg/year
$H_{2,ADWfs}$	H_2 from AD of waste first stage	kg/year
$H_{2,h}$	H_2 required for domestic heating	kg/year
$H_{2,ph}$	H_2 required for process heating	kg/year
$H_{2,SMRM}$	H_2 from SMR of methane produced from AD of miscanthus, second stage	kg/year
$H_{2,SMRW}$	H_2 from SMR of methane produced from AD of waste, second stage	kg/year
$H_{2,t}$	H_2 required for transport	kg/year
$H_{2,tot}$	Total H_2 required	kg/year
$H_{2,totM}$	Total H_2 generated from miscanthus	kg/year
$H_{2,totW}$	Total H_2 generated from waste	kg/year
$H_{2,WE}$	H_2 required from WE	kg/year
H_2O_{WE}	Water required for WE	kg/year
H_2O_{SMR}	Water required for SMR	kg/year
HHV_{CH4}	Calorific value of methane	J/kg
HHV_{H2}	Calorific value of hydrogen	J/kg
L_{km}	Total distance travelled in the UK	km/year
$L_{km/H2}$	Distance travelled per unit of hydrogen fuel	km/kg
$L_{km/CH4}$	Distance travelled per unit of methane fuel	km/kg
$L_{km/Et}$	Mileage for electric cars	km/J
M	Production rate of miscanthus	kg/year
OFMSW	Organic fraction of municipal solid waste	
SMR	Steam methane reforming	
VS	Volatile solids	
W	Generation rate of organic waste	kg/year
WE	Water electrolysis	
$Y_{ADCH4/M}$	Yield of methane from miscanthus, AD single stage	kg/kg
$Y_{ADCH4/W}$	Yield of methane from waste, AD single stage	kg/kg
$Y_{ADfsH2/M}$	Yield of H_2 from miscanthus, AD first stage	kg/kg
$Y_{ADfsH2/W}$	Yield of H_2 from waste, AD first stage	kg/kg
$Y_{ADssCH4/M}$	Yield of CH_4 from miscanthus, AD second stage	kg/kg
$Y_{ADssCH4/W}$	Yield of CH_4 from waste, AD second stage	kg/kg
$Y_{M/A}$	Miscanthus growth rate per unit land area	t/ha.year
$Y_{SMRH2/CH4}$	Yield of H_2 from CH_4, SMR	kg/kg
$Y_{SMRH2O/H2}$	Water required per unit H_2, SMR	kg/kg
$Y_{WEH2O/H2}$	Water required per unit H_2, WE	kg/kg
η_{CHP}	Efficiency of CHP conversion into electricity	

1. Introduction

The use of renewable energy for electricity generation in the EU has increased rapidly in recent years, mainly thanks to the increased use of solar and wind energy [1]. On the other hand, the use of renewable energy in the transport and household sectors, which account respectively for 31 and 27 % of the total final energy consumption in the EU, is still limited [2]. In the EU in 2018, renewable resources were used to generate 32 % of the electricity but just 8 % of the energy used for transport and 23 % of the energy used by the household sector (excluding electricity) [2]. In the household sector, most of the energy (78 %) is required for space and water heating [3], which in the EU is mainly provided by natural gas and other fossil fuels. Natural gas and other fossil fuels account for approximately 70 % of the non-electrical household energy consumption [2,3]. As a result, the contribution of renewable energy, including biomass, solar, wind, marine, geothermal and hydro energy, to the total final energy consumption in the EU in 2018 was limited to approximately 20 % [2]. Increasing the share of renewable energy used in the transport sector and for domestic heating is therefore essential.

Various technologies and processes, at different development stages, can be in principle considered for the generation of renewable energy for heating and transportation. For example, solar photovoltaic panels and wind turbines can generate renewable electricity for electric vehicles and for heating via heat pumps or resistive heating [4]. Anaerobic digestion (AD) of organic waste or energy crops can generate renewable methane for electricity, heating or transportation. Hydrogen can be used as a renewable energy vector when it is generated from water electrolysis (WE) using renewable electricity. Renewable hydrogen can also be generated from biomass using gasification or pyrolysis or using anaerobic digestion, which can produce hydrogen either directly as an intermediate of the anaerobic metabolism of the microorganisms [5,6], or indirectly via steam reforming of the methane (steam methane reforming, SMR). The chemical energy of hydrogen can be converted into energy for domestic heating using various technologies, e.g. fuel cell micro-CHP, direct flame combustion boilers, catalytic boilers and into energy for transportation using fuel cells or hydrogen fuelled internal combustion engines [7,8].

Various constraints have so far limited a wider uptake of renewable energy for transport and household heating. An important factor is the land requirement of renewable energy technologies [9], which has been considered in several studies [10-13]. Land is required to generate renewable electricity, to be used directly in electric vehicles or indirectly for hydrogen generation via WE and for the growth of energy crops to be used in AD. Since land availability is limited, it is important to compare the land requirements of the various processes for renewable energy generation. Water is another requirement in some processes for renewable energy generation. Considering only the direct use of water, and not the water uses in the life cycle of renewable energy technologies, water is required in WE and in SMR for methane conversion into hydrogen. Although water is released back into the environment when hydrogen is combusted to generate energy, water is released in the vapour phase and will not go directly back to the source of liquid water from which it was extracted. Therefore, water consumption of renewable energy processes needs to be considered and compared as water resources are limited.

Without attempting to consider all the possible processes and technologies, this study calculates and compares the land and water requirements for the supply of all domestic heating and road transport energy in the UK using WE for hydrogen production and AD of organic waste and energy crops. This study also includes the heat and electricity needed by the energy conversion processes. For AD, both the single stage process for methane production and the two-stage process for hydrogen and methane production are considered. The hydrogen produced from WE and/or AD is assumed to be used in fuel cell vehicles for transport and in boilers for domestic heating. The results are also compared with the direct use of electricity for battery electric vehicles. While the results of this study are valid for the UK, the methodology used can also be applied to other countries. The novelty of this study can be summarised as follows: 1) quantitative analysis of the potential generation of renewable energy for heating and transport in the UK; 2) quantitative analysis of the potential role of WE and AD in renewable energy scenarios; 3) quantitative consideration of the energy requirements of the conversion processes, in addition to the energy requirements for heating and transport. This study, which, to the best of our knowledge, has not been carried out before, aims to contribute to a critical analysis of the feasibility of achieving 100 % renewable energy use. This study is not aimed at a life cycle assessment of the various scenarios and at a long-term analysis of the techno-economic feasibility of the scenarios. These are important aspects which should be considered alongside the results of this study for a complete assessment of the various scenarios for a renewable energy future.

2. Considered scenarios

The scenarios considered in this study for the generation of renewable heat and transport energy are shown in Figure 1. All scenarios use hydrogen and/or methane as energy vectors but with different hydrogen generation technologies. Hydrogen has been considered in this study because it is an emerging and promising vector for energy conversion and storage due to its high calorific value per unit mass and to the possibility of its generation from renewable resources. Hydrogen is assumed to be generated by WE and/or by AD. For AD, either a two-stage process with hydrogen (first stage) and methane (second stage) production or a single stage process with methane production only is considered [14]. The AD feed is assumed to be made of either organic waste only or organic waste and miscanthus, where miscanthus is used as an example energy crop to provide the balance of the required energy (see section 3.1). Hydrogen is assumed to be used for domestic heating using combustion boilers and for transportation using fuel cell vehicles.

The technologies considered in these scenarios are at different development stages, and for some of them technical advances are required to achieve full scale deployment. AD for methane production is widely used at commercial scale in the UK and globally. However, two-stage AD for hydrogen and methane production is still at the development and pilot stage [14]. WE for hydrogen production is used at small commercial scale, even though it only contributes to a small fraction (approximately 4 % [15]) of current hydrogen production, which mainly comes from SMR of natural gas. The use of hydrogen for transport in fuel cell vehicles is mainly used in demonstration projects [16]. Methane is widely used for domestic heating (mainly from natural gas) but has only limited use so far for vehicle applications [17]. Hydrogen is not currently used for domestic heating at commercial scale, but several demonstration projects have been proposed or are under way to establish the safety of using 100 % hydrogen in houses and hydrogen-natural gas mixtures of up to 20 % hydrogen v/v can be accepted in domestic heating systems without modifications [18,19]. It is however important to observe that hydrogen combustion can generate some forms of greenhouse gases, NOx, due to the high temperature. However, their formation can be reduced by catalytic combustion processes [20].

In Scenario 1, hydrogen is the only energy vector for transport and heating. Hydrogen is generated entirely from AD of waste and miscanthus in the two-stage process. The methane produced in the second stage is converted to hydrogen via SMR.

In Scenario 2, hydrogen is still the only energy vector for transport and heating but is generated entirely via WE.

In Scenario 3 the energy for transport is provided by hydrogen generated by WE, while the energy for heating is provided by methane generated by AD of waste and miscanthus.

Scenario 4 uses hydrogen for transport and a mixture of hydrogen and methane for heating. In this scenario, AD uses waste to produce hydrogen and methane and the balance of the energy is provided by hydrogen generated by WE.

In Scenario 5 hydrogen is the only energy vector for transport and heating and is generated entirely by WE. In this scenario, waste is converted to methane in a single stage AD and methane is converted to electricity in a CHP unit which generates electricity for WE and heat.

Scenario 6 is similar to Scenario 4 except that the methane produced by AD is converted to hydrogen by SMR.

In Scenario 7 hydrogen, produced by AD of waste and by WE, is still the only energy vector. In AD, only the first stage (hydrogen production) is used for energy generation, while the effluent from the first stage (rich in short chain organic acids, SCOAs) is potentially available for the chemical industry or for other uses.

In Scenario 8 methane is the only energy vector and is produced entirely by the AD of waste and miscanthus.

In Scenario 9, the energy for transport is the electricity used directly in battery electric vehicles, while the energy for heat is provided by hydrogen generated by WE and AD (first stage) and by methane generated by AD (second stage). In this scenario, AD uses waste only.

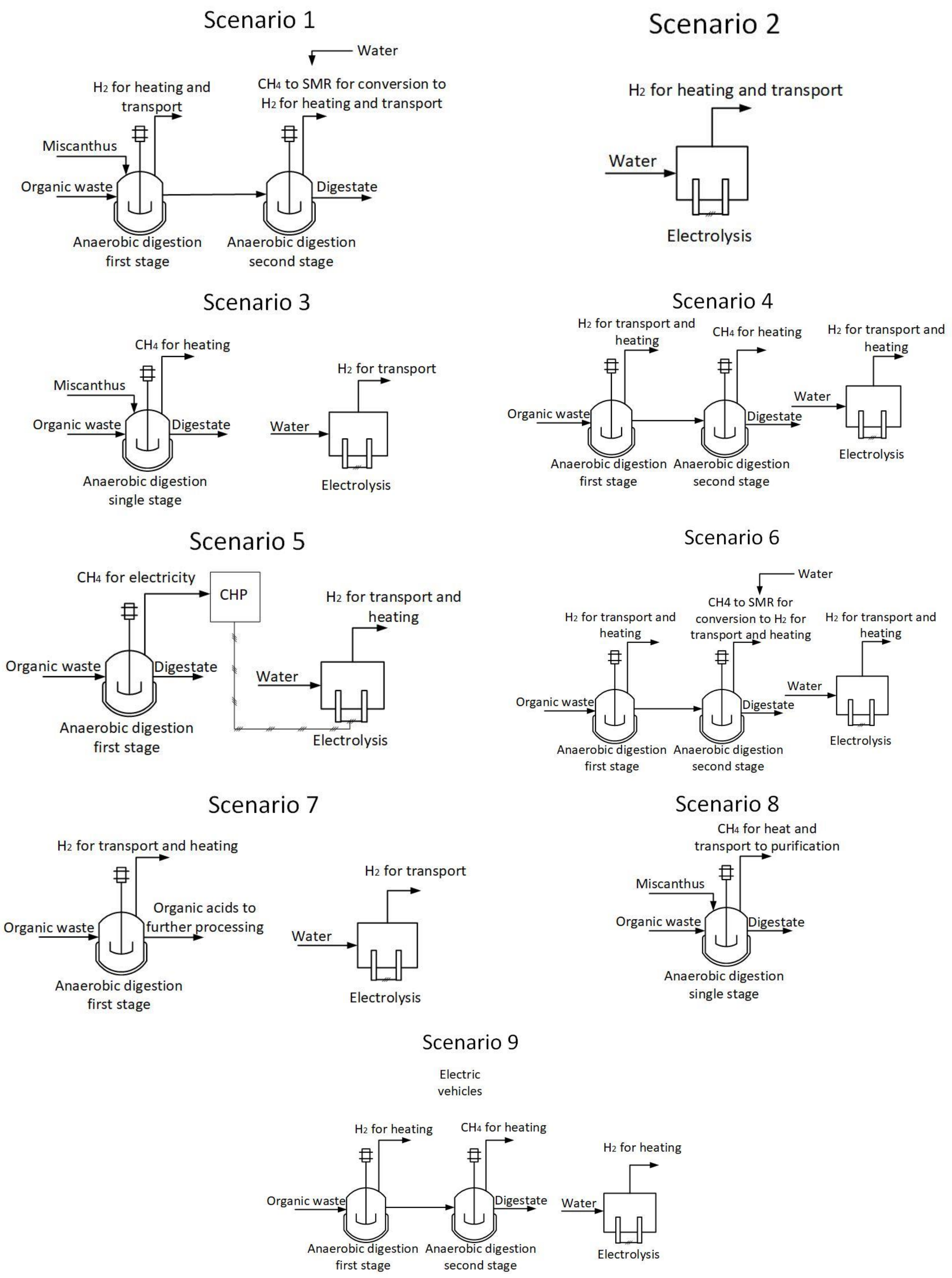

Figure 1. The nine scenarios for the renewable supply of heating and transport energy considered in this study. The scenarios are explained in the text.

3. Methodology

3.1 Assumptions used in the calculations

The following assumptions have been made in this study:

- For simplicity’s sake, onshore solar PV panels are assumed to generate all the electricity for all the scenarios. Other technologies are also possible for the generation of renewable electricity, for example onshore and offshore wind turbines. However, some studies show that more electricity is generated per unit land by solar PV panels than by wind turbines [11, 21]. Furthermore, the solar PV capacity is increasing worldwide (and in the UK) thanks to increasing the efficiency of the solar PV panels and reducing the cost. Therefore, solar PV has been selected as the electricity source in this study for its potential to become a main energy source in the near future. However, the calculations done in this study can be easily adapted to consider the land requirements of other renewable energy sources such as wind turbines;
- The feedstocks for AD are assumed to be either only organic waste, or organic waste and miscanthus. Miscanthus is chosen as an example of energy crop, as it grows well in the UK with high yield and is already in use as energy crop [22]. The calculated results can be easily adapted for other energy crops. The annual generation of organic waste is assumed to be a fixed value, while miscanthus, when used, is assumed to provide the balance of the energy to be provided by AD;
- Hydrogen or methane (depending on the scenarios) are assumed to provide the energy for domestic heating and road transport (except for scenario 9 where battery electric vehicles are used), and also the heating energy (process heating

energy) for miscanthus growth, AD, CO_2 removal, and SMR processes. Electricity is assumed to be used for miscanthus growth, AD, CO_2 removal, SMR, hydrogen or methane compression (only for the gases used for transport), WE, and battery electric vehicles. Any other consumption of heat or electricity, like the heat and electricity required for hydrogen or methane purification (apart from CO_2 removal) and the energy required for waste and miscanthus transportation to the AD plants, is ignored;

- The land requirements include only the area for PV panels and for miscanthus growth, and any other land requirements, like the land occupied by the AD or WE plant, is ignored. Only the direct water consumption due to SMR and WE is considered and any indirect water consumption which occurs in the life cycle of the considered technologies is ignored.

Since this study is aimed at the calculation of the land and water requirements, other factors, such as full energy balances, emissions of carbon dioxide and waste and other potential environmental impacts are not considered. These are however important aspects which need to be considered for a full appreciation of the implications of each technology.

3.2 Calculations

The numerical parameters used in the calculations are reported in Table 1. The calculations for the different scenarios are reported in this section. We use the same methodology in all the scenarios, but, since the scenarios are different, we report the calculations separately for each scenario. The key novelty of the theoretical approach used here is that, in addition to the energy required for heating and transport, we also calculate the energy and land requirements of the conversion processes. This methodology, which, to the best of our knowledge has not been used before in this sector, can also be used for other renewable energy scenarios not considered in this study.

3.2.1 Scenario 1

The total hydrogen required ($H_{2,tot}$), the hydrogen required for domestic heat ($H_{2,h}$) and the hydrogen required for transport ($H_{2,t}$) are calculated from Equations (1), (2) and (3), respectively.

$$H_{2,tot} = H_{2,h} + H_{2,t} + H_{2,ph} \tag{1}$$

$$H_{2,h} = \frac{E_{h,d}}{HHV_{H2}} \tag{2}$$

$$H_{2,t} = \frac{L_{km}}{L_{km/H2}} \tag{3}$$

The hydrogen required for process heat $H_{2,ph}$ depends on the total required hydrogen, according to Equation (4), which, combined with Equation (1), gives Equation (5).

$$H_{2,ph} = \frac{E_{h,ph/H2}}{HHV_{H2}} H_{2,tot} \tag{4}$$

$$H_{2,tot} = \frac{H_{2,h} + H_{2,t}}{1 - \frac{E_{h,ph/H2}}{HHV_{H2}}} \tag{5}$$

The process heat per unit of total hydrogen, $E_{h,ph/H2}$, is calculated as the weighted average of the process heat per unit hydrogen for the various processes (AD, miscanthus growth, SMR, CO_2 removal), considering the fraction of the hydrogen generated via the respective process, Equation (6).

$$E_{h,ph/H2} = \frac{\begin{pmatrix} E_{h,phWfs/H2} H_{2,ADWfs} + E_{h,phWss/H2} H_{2,SMRW} + \\ E_{h,phMfs/H2} H_{2,ADMfs} + E_{h,phMss/H2} H_{2,SMRM} \end{pmatrix}}{H_{2,tot}} \tag{6}$$

In Equation (6), the terms of the process heat per unit hydrogen for the hydrogen generated from waste or miscanthus in the first ($E_{h,phWfs/H2}$, $E_{h,phMfs/H2}$), or in the second AD stage after SMR ($E_{h,phWss/H2}$, $E_{h,phMss/H2}$), are calculated from Equations (7)-(10).

$$E_{h,phWfs/H2} = E_{h,ADWfs/H2} + E_{h,CO2/H2} \tag{7}$$

$$E_{h,phWss/H2} = E_{h,ADWss/H2} + E_{h,SMR/H2} + E_{h,CO2/H2} \tag{8}$$

$$E_{h,phMfs/H2} = E_{h,Mgrowth/H2} + E_{h,ADMfs/H2} + E_{h,SMR/H2} + E_{h,CO2/H2} \tag{9}$$

$$E_{h,phMss/H2} = E_{h,Mgrowth/H2} + E_{h,ADMss/H2} + E_{h,SMR/H2} + E_{h,CO2/H2} \tag{10}$$

The hydrogen generated from the first and second stage (after SMR) and the total hydrogen from waste are calculated from Equations (11)-(14).

$$H_{2,ADWfs} = WY_{ADfsH2/W} \tag{11}$$

$$CH_{4,ADWss} = WY_{ADssCH4/W} \tag{12}$$

$$H_{2,SMRW} = CH_{4,ADWss}Y_{SMRH2/CH4} \tag{13}$$

$$H_{2,totW} = H_{2,ADWfs} + H_{2,SMRW} \tag{14}$$

The hydrogen required from miscanthus is calculated from Equation (15).

$$H_{2,totM} = H_{2,tot} - H_{2,totW} \tag{15}$$

For miscanthus, the hydrogen from the first and second AD stage, and the total hydrogen are calculated from Equations (16)-(19).

$$H_{2,ADMfs} = MY_{ADfsH2/M} \tag{16}$$

$$CH_{4,ADMss} = MY_{ADssCH4/M} \tag{17}$$

$$H_{2,SMRM} = CH_{4,ADMss}Y_{SMRH2/CH4} \tag{18}$$

$$H_{2,totM} = H_{2,ADMfs} + H_{2,SMRM} \tag{19}$$

Combining Equations (15)-(19), the annual required amount of miscanthus, *M*, is calculated from Equation (20).

$$M = \frac{H_{2,tot} - H_{2,totW}}{Y_{ADfsH2/M} + Y_{ADssCH4/M} Y_{SMRH2/CH4}} \quad (20)$$

Equations (5), (6) and (20) constitute a system of three equations in the three unknowns $H_{2,tot}$, M and $E_{h,ph/H2}$, which is solved iteratively.

The land required for miscanthus growth is calculated from Equation (21).

$$A_M = \frac{M}{Y_{M/A}} \quad (21)$$

The required electricity is calculated in a similar way as the process heat, by adapting Equation (6) to account for the electricity requirements of the hydrogen generated from waste and from miscanthus, from the first AD stage or from SMR of the methane produced in the second stage. The electricity required per unit hydrogen is given by Equation (22).

$$E_{el/H2} = \frac{\begin{pmatrix} E_{el,Wfs/H2} H_{2,ADWfs} + E_{el,Wss/H2} H_{2,SMRW} \\ + E_{el,Mfs/H2} H_{2,ADMfs} + E_{el,Mss/H2} H_{2,SMRM} \end{pmatrix}}{H_{2,tot}} \quad (22)$$

The contributions to the electricity requirements per unit hydrogen are calculated from Equations (23)-(26).

$$E_{el,Wfs/H2} = E_{el,ADWfs/H2} + E_{el,CO2/H2} + E_{el,H2comp/H2} \quad (23)$$

$$E_{el,Wss/H2} = E_{el,ADWss/H2} + E_{el,SMR/H2} + E_{el,CO2/H2} + E_{el,H2comp/H2} \quad (24)$$

$$E_{el,Mfs/H2} = E_{el,Mgrowth/H2} + E_{el,ADMfs/H2} + E_{el,SMR/H2} + E_{el,CO2/H2} + E_{el,H2comp/H2} \quad (25)$$

$$E_{el,Mss/H2} = E_{el,Mgrowth/H2} + E_{el,ADMss/H2} + E_{el,SMR/H2} + E_{el,CO2/H2} + E_{el,H2comp/H2} \quad (26)$$

In Equations (23)-(26) the term $E_{elH2comp/H2}$ is proportionally reduced, compared to the value in Table 1, to account for the fact that only a fraction of the hydrogen is used for transport and therefore needs compression.

The total electricity is calculated from Equation (27).

$$E_{el,tot} = E_{el/H2} H_{2,tot} \quad (27)$$

The land required for solar PV panels to supply the total electricity requirements is calculated from Equation (28). In a similar way, the contributions of the various processes (AD, SMR, miscanthus growth, CO_2 removal, hydrogen compression) to the electricity and land requirements, is calculated.

$$A_{PV,tot} = \frac{E_{el,tot}}{E_{PV}} \tag{28}$$

The total land required is calculated as the sum of the total land for PV panels and of the area required for miscanthus growth, Equation (29).

$$A_{tot} = A_M + A_{PV,tot} \tag{29}$$

The total energy required is calculated by adding up the energy generated by the combustion of hydrogen and the total electricity required, Equation (30).

$$E_{tot} = H_{2,tot} HHV_{H2} + E_{el,tot} \tag{30}$$

The water required for SMR is calculated from Equation (31).

$$H_2O_{SMR} = \left(H_{2,SMRW} + H_{2,SMRM}\right) Y_{SMRH2O/H2} \tag{31}$$

3.2.2 Scenario 2

The total hydrogen required is calculated using Equations (1)-(3), but without the term for the hydrogen for process heat. The electricity requirements are the sum of the requirements for WE and for hydrogen compression, Equations (32)-(34).

$$E_{el,WE} = E_{el,WE/H2} H_{2,tot} \tag{32}$$

$$E_{el,H2comp} = E_{el,H2comp/H2} H_{2,t} \tag{33}$$

$$E_{el,tot} = E_{el,WE} + E_{el,H2comp} \tag{34}$$

The total land requirement is only due to PV panels and is calculated with Equation (28). The total energy requirement coincides with the total electricity requirement. The water requirement is only due to WE and is calculated from Equation (35).

$$H_2O_{WE} = H_{2,tot}Y_{WEH2O/H2} \quad (35)$$

3.2.3 Scenario 3

The hydrogen for transport is calculated using Equation (3). The methane required for domestic heat is calculated from Equation (36).

$$CH_{4,h} = \frac{E_{h,d}}{HHV_{CH4}} \quad (36)$$

The total methane required, considering the requirements for process heat, is calculated from Equation (37).

$$CH_{4,tot} = CH_{4,h} + CH_{4,ph} \quad (37)$$

In analogy with Scenario 1, Equation (4), we express the methane required for process heat as a function of the total methane required, Equation (38).

$$CH_{4,ph} = \frac{E_{h,ph/CH4}}{HHV_{CH4}} CH_{4,tot} \quad (38)$$

Combining Equations (37) and (38), in analogy with Scenario 1, we obtain Equation (39).

$$CH_{4,tot} = \frac{CH_{4,h}}{1 - \frac{E_{h,ph/CH4}}{HHV_{CH4}}} \quad (39)$$

In analogy with Scenario 1, the process heat per unit methane, $E_{h,ph/CH4}$, is calculated as the weighted average of the process heat per unit methane for the methane derived from waste and from miscanthus, Equation (40).

$$E_{h,ph/CH4} = \frac{\left(E_{h,phW/CH4}CH_{4,ADW} + E_{h,phM/CH4}CH_{4,ADM}\right)}{CH_{4,tot}} \quad (40)$$

In analogy with Scenario 1, Equations (7)-(10), the terms $E_{h,phW/CH4}$ and $E_{h,phM/CH4}$ are calculated from Equations (41) and (42).

$$E_{h,phW/CH4} = E_{h,ADW/CH4} + E_{h,CO2/CH4} \quad (41)$$

$$E_{h,phM/CH4} = E_{h,Mgrowth/CH4} + E_{h,ADM/CH4} + E_{h,CO2/CH4} \quad (42)$$

The methane from waste and the methane required from miscanthus are calculated from Equations (43) and (44).

$$CH_{4,ADW} = WY_{ADCH4/W} \tag{43}$$

$$CH_{4,ADM} = CH_{4,tot} - CH_{4,ADW} \tag{44}$$

The methane produced from miscanthus in single stage AD is given by Equation (45).

$$CH_{4,ADM} = MY_{ADCH4/M} \tag{45}$$

The miscanthus required is calculated by combining Equations (44) and (45) into Equation (46).

$$M = \frac{CH_{4,tot} - CH_{4,ADW}}{Y_{ADCH4/M}} \tag{46}$$

In analogy with Scenario 1, Equations (39), (40) and (46) are a system of three equations in the three unknowns CH_{4tot}, M and $E_{h,ph/CH4}$, which is solved iteratively.

The land required for miscanthus growth was calculated with Equation (21).

The electricity requirement for WE and hydrogen compression, $E_{el,WE}$ and $E_{el,H2comp}$, are calculated from Equations (32) and (33), considering only the hydrogen for transport.

The electricity requirement for the methane produced from AD is calculated from Equations (47)-(50).

$$E_{el,CH4} = E_{el,CH4/CH4} CH_{4,tot} \tag{47}$$

$$E_{el,CH4/CH4} = \frac{\left(E_{el,CH4W/CH4} \cdot CH_{4,ADW} + E_{el,CH4M/CH4} \cdot CH_{4,ADM}\right)}{CH_{4,tot}} \tag{48}$$

$$E_{el,CH4W/CH4} = E_{el,ADW/CH4} + E_{el,CO2/CH4} \tag{49}$$

$$E_{el,CH4M/CH4} = E_{el,Mgrowth/CH4} + E_{el,ADM/CH4} + E_{el,CO2/CH4} \tag{50}$$

The total electricity requirement is calculated from Equation (51).

$$E_{el,tot} = E_{el,WE} + E_{el,H2comp} + E_{el,CH4} \tag{51}$$

The land area for solar PV panels and the total land area are calculated with Equations (28) and (29). The total energy requirement is calculated with Equation (52).

$$E_{tot} = CH_{4,tot}HHV_{CH4} + E_{el,tot} \tag{52}$$

The water is required for WE only and was calculated with Equation (35), considering only the hydrogen required for transport.

3.2.4 Scenario 4

The total hydrogen required is calculated from Equation (53).

$$H_{2,tot} = H_{2,h} - \frac{CH_{4,ADWss} \cdot HHV_{CH4}}{HHV_{H2}} + H_{2,t} + H_{2,ph} \tag{53}$$

The hydrogen for domestic heat and for transport is calculated using Equations (2) and (3). The methane from the second AD stage, $CH_{4,ADWss}$, is calculated with Equation (12). The hydrogen required for the process heating energy is calculated from Equation (54).

$$H_{2,ph} = \frac{E_{h,ph}}{HHV_{H2}} \tag{54}$$

The process heating energy, $E_{h,ph}$, is calculated with Equation (55).

$$E_{h,ph} = E_{h,ADWfs/H2}H_{2,ADWfs} + E_{h,ADWss/CH4}CH_{4,ADWss} + E_{h,CO2/CH4}CH_{4,ADWss} \tag{55}$$

The hydrogen from the AD first stage, $H_{2,ADWfs}$, is calculated with Equation (11). The hydrogen required from WE, $H_{2,WE}$, is calculated from the total hydrogen required minus the hydrogen from AD of waste first stage, Equation (56).

$$H_{2,WE} = H_{2,tot} - H_{2,ADWfs} \tag{56}$$

The electricity requirements are calculated as the sum of the electricity requirements for WE, for hydrogen compression, for CO_2 removal and for AD, Equations (57)-(61).

$$E_{el,tot} = E_{el,WE} + E_{el,H2comp} + E_{el,CO2} + E_{el,AD} \tag{57}$$

$$E_{el,WE} = E_{el,WE/H2}H_{2,WE} \tag{58}$$

$$E_{el,H2comp} = E_{el,comp/H2}\left(H_{2,WE} + H_{2,ADWfs}\right) \tag{59}$$

$$E_{el,CO2} = E_{el,CO2/H2}H_{2,ADWfs} + E_{el,CO2/CH4}CH_{4,ADWss} \tag{60}$$

$$E_{el,AD} = E_{el,ADWfs/H2}H_{2,ADWfs} + E_{el,ADWss/CH4}CH_{4,ADWss} \tag{61}$$

The land required for electricity generation is calculated with Equation (28).

The total energy required is calculated by adding up the energy generated by the combustion of hydrogen and of methane and the total electricity required, Equation (62).

$$E_{tot} = H_{2,ADWfs}HHV_{H2} + CH_{4,ADWss}HHV_{CH4} + E_{el,tot} \tag{62}$$

The water was required for WE only and is calculated with Equation (35), considering only the hydrogen to be provided by WE, $H_{2,WE}$.

3.2.5 Scenario 5

The total hydrogen required is calculated with Equation (63), which modifies Equation (1) taking the heating energy obtained from the CHP into account. In Equation (63), it is assumed that all the combustion energy of the methane that is not converted into electricity is used for heating.

$$H_{2,tot} = H_{2,h} + H_{2,t} + H_{2,ph} - \frac{CH_{4,ADW}(1-\eta_{CHP})HHV_{CH4}}{HHV_{H2}} \tag{63}$$

The terms $H_{2,h}$ and $H_{2,t}$ are calculated according to Equations (2) and (3). The term $H_{2,ph}$ is calculated with Equations (64), (65) and (43).

$$H_{2,ph} = \frac{E_{h,ph}}{HHV_{H2}} \tag{64}$$

$$E_{h,ph} = E_{h,ADW/CH4}CH_{4,ADW} \tag{65}$$

The electricity required is calculated with Equation (66), which includes the electricity generated by the combustion of methane generated by AD.

$$E_{el,tot} = E_{el,WE} + E_{el,AD} + E_{el,H2comp} - CH_{4,ADW}\eta_{CHP}HHV_{CH4} \tag{66}$$

The terms $E_{el,WE}$, $E_{el,H2comp}$, $CH_{4,ADW}$ are calculated with Equations (32), (33), (43), respectively. The term $E_{el,AD}$ is calculated with Equation (67).

$$E_{el,AD} = E_{el,ADW/CH4} CH_{4,ADW} \tag{67}$$

The land required for electricity is calculated with Equation (28). The total energy required is calculated with Equation (52). The water requirement is calculated with Equation (35).

3.2.6 Scenario 6

The total hydrogen required is calculated with Equations (1)-(3). The hydrogen for process heat is calculated with Equation (64), with the term $E_{h,ph}$ given by Equation (68).

$$E_{h,ph} = E_{h,ADWfs/H2} H_{2,ADWfs} + E_{h,ADWss/CH4} CH_{4,ADWss} + E_{h,SMR/H2} CH_{4,ADWss} Y_{SMRH2/CH4} +$$

$$E_{h,CO2/CH4} CH_{4,ADWss} \tag{68}$$

In Equation (68), the terms $H_{2,ADWfs}$ and $CH_{4,ADWss}$ are calculated with Equations (11) and (12), respectively.

The electricity requirement is calculated from Equation (69).

$$E_{el,tot} = E_{el,WE} + E_{el,H2comp} + E_{el,CO2} + E_{el,SMR} + E_{el,AD} \tag{69}$$

The term $E_{el,WE}$ is calculated with Equation (58), with $H_{2,WE}$ given by Equation (70).

$$H_{2,WE} = H_{2,tot} - H_{2,ADWfs} - H_{2,SMRW} \tag{70}$$

In Equation (70), the term $H_{2,SMRW}$ is calculated with Equations (12) and (13). The term $E_{el,H2comp}$ is calculated with Equation (33) and $E_{el,AD}$ with Equation (61). The term $E_{el,CO2}$ is calculated from Equation (71).

$$E_{el,CO2} = E_{el,CO2/H2}\left(H_{2,ADWfs} + H_{2,SMRW}\right) \tag{71}$$

The total land required, which coincides with the land required for solar PV for electricity generation, is calculated with Equation (28). Water is required for WE and for SMR and is calculated by adding up the contributions of these processes.

3.2.7 Scenario 7

The total hydrogen required is calculated with Equations (1)-(3). The hydrogen for process heat is calculated with Equation (64). The process heating energy is calculated from Equation (72), with $H_{2,ADWfs}$ given by Equation (11).

$$E_{h,ph} = \left(E_{h,ADWfs/H2} + E_{h,CO2/H2}\right)H_{2,ADWfs} \tag{72}$$

The hydrogen required from WE is calculated from Equation (56).

The total electricity requirement is calculated with Equation (57). The electricity required for WE is calculated with Equation (58) and the electricity for compression with Equation (33). The electricity required for CO_2 removal is calculated from Equation (73). The electricity required for AD is calculated from Equation (74).

$$E_{el,CO2} = E_{el,CO2/H2}H_{2,ADWfs} \tag{73}$$

$$E_{el,AD} = E_{el,ADWfs/H2}H_{2,ADWfs} \tag{74}$$

The total land required, which coincided with the land required for solar PV for electricity generation, is calculated with Equation (28) and the water requirement with Equation (35), considering only the hydrogen to be provided by WE, $H_{2,WE}$.

3.2.8 Scenario 8

The total methane required is calculated Equation (75).

$$CH_{4,tot} = CH_{4,h} + CH_{4,t} + CH_{4,ph} \tag{75}$$

The methane required for heating, $CH_{4,h}$, is calculated with Equation (36) and the methane required for transport with Equation (76).

$$CH_{4,t} = \frac{L_{km}}{L_{km/CH4}} \tag{76}$$

The methane required for process heat, $CH_{4,ph}$, is calculated with Equation (38). Combining Equation (38) with Equation (75) we obtain Equation (77) for $CH_{4,tot}$.

$$CH_{4,tot} = \frac{CH_{4,h} + CH_{4,t}}{1 - \frac{E_{h,ph/CH4}}{HHV_{CH4}}} \tag{77}$$

In analogy with Scenario 3, the term $E_{h,ph/CH4}$, the methane produced from waste and the miscanthus required are calculated with Equations (40)-(46). Equations (77), (40) and (46) constitute a system of three equations in the three unknowns $CH_{4,tot}$, $E_{h,ph/CH4}$ and M. The land required for miscanthus growth is calculated with Equation (21).

The total electricity required is due to AD, CO_2 removal and CH_4 compression, and is calculated with Equation (51) (without the terms for WE and hydrogen compression), (47), (48) and with Equations (78), (79) which replace Equations (49), (50) by including the term for methane compression.

$$E_{el,CH4W/CH4} = E_{el,ADW/CH4} + E_{el,CO2/CH4} + E_{el,CH4comp/CH4} \tag{78}$$

$$E_{el,CH4M/CH4} = E_{el,Mgrowth/CH4} + E_{el,ADM/CH4} + E_{el,CO2/CH4} + E_{el,CH4comp/CH4} \tag{79}$$

The land area for solar PV panels and the total land area are calculated with Equations (28) and (29). The total energy requirement is calculated with Equation (52). There is no water requirement in this scenario.

3.2.9 Scenario 9

The total hydrogen required is calculated with Equation (80).

$$H_{2,tot} = H_{2,h} - \frac{CH_{4,ADWss} HHV_{CH4}}{HHV_{H2}} + H_{2,ph} \tag{80}$$

In Equation (80), the terms $H_{2,h}$ and $CH_{4,ADWss}$ are calculated with Equations (2) and (12), respectively. The hydrogen for process heat is calculated from Equations (54) and (55), with $H_{2,ADWfs}$ and $CH_{4,ADWss}$ given by Equations (11) and (12).

The total electricity required is given by Equation (81).

$$E_{el,tot} = E_{el,WE} + E_{el,CO2} + E_{el,AD} + E_{el,t} \tag{81}$$

In Equation (81), the term $E_{el,t}$ is given by Equation (82), the term $E_{el,WE}$ by Equations (56) and (58), the term $E_{el,CO2}$ by Equation (60) and the term $E_{el,AD}$ by Equation (61).

$$E_{el,t} = \frac{L_{km}}{L_{km/Et}} \tag{82}$$

The total area required is only due to PV panels, and is given by Equation (28). The total energy required is given by Equation (62). The water is required for WE only and is calculated with Equation (35), considering only the hydrogen to be provided by WE, $H_{2,WE}$.

Table 1. Numerical parameters used in this study (base case)

Parameter	Value	Reference
$E_{el,ADM/CH4}$	6,155 MJ/t_{CH4}	Calculated assuming electrical energy requirements in AD of 1,000 MJ/t_{VS} [23] and the assumed yields of H_2 and CH_4 production from waste and miscanthus. For the two stage AD process, half of the total electricity consumption is assumed for each stage
$E_{el,ADMfs/H2}$	40,734 MJ/t_{H2}	
$E_{el,ADMss/H2}$	7,251 MJ/t_{H2}	
$E_{el,ADW/CH4}$	4,999 MJ/t_{CH4}	
$E_{el,ADWfs/H2}$	36,532 MJ/t_{H2}	
$E_{el,ADWss/CH4}$	2,895 MJ/t_{CH4}	
$E_{el,ADWss/H2}$	5,791 MJ/t_{H2}	
$E_{el,CH4comp/CH4}$	1,277 MJ/t_{CH4}	Calculated from [24]
$E_{el,CO2/CH4}$	681 MJ/t_{CH4}	Calculated from [25]
$E_{el,CO2/H2}$	2,140 MJ/t_{H2}	Calculated from [25]
$E_{el,H2comp/H2}$	17,015 MJ/t_{H2}	Calculated from [26]
$E_{el,Mgrowth/CH4}$	2,804 MJ/t_{CH4}	Calculated from [27]
$E_{el,Mgrowth/H2}$	5,608 MJ/t_{H2}	Calculated from [27]
$E_{el,SMR/H2}$	1,144 MJ/t_{H2}	Calculated from [28]
$E_{el,WE/H2}$	182,022 MJ/t_{H2}	Calculated from [29]
$E_{h,ADM/CH4}$	6,155 MJ/t_{CH4}	Calculated assuming heating energy requirements in AD of 1,000 MJ/t_{VS} [23] and the assumed yields of H_2 and CH_4 production from waste and miscanthus. For the two stage AD process, half of the total heating energy consumption is assumed for each stage
$E_{h,ADMfs/H2}$	40,734 MJ/t_{H2}	
$E_{h,ADMss/H2}$	7,251 MJ/t_{H2}	
$E_{h,ADW/CH4}$	4,999 MJ/t_{CH4}	
$E_{h,ADWfs/H2}$	36,532 MJ/t_{H2}	
$E_{h,ADWss/CH4}$	2,986 MJ/t_{CH4}	
$E_{h,ADWss/H2}$	5,791 MJ/t_{H2}	
$E_{h,CO2/CH4}$	3,911 MJ/t_{CH4}	Calculated from [25]
$E_{h,CO2/H2}$	12,290 MJ/t_{H2}	Calculated from [25]
$E_{h,d}$	1.345 EJ/year	Calculated from [30]
$E_{h,Mgrowth/CH4}$	3,250 MJ/t_{CH4}	Calculated from [27]
$E_{h,Mgrowth/H2}$	6,502 MJ/t_{H2}	Calculated from [27]
$E_{h,SMR/H2}$	17,600 MJ/t_{H2}	Calculated from [28]
E_{PV}	$1.84 \cdot 10^6$ MJ/ha.year	Calculated from [21], which uses an average power capacity per unit area of 54.2 MW/km^2 and a load factor of 0.1076
HHV_{H2}	141,790 MJ/t_{H2}	[31]
HHV_{CH4}	55,500 MJ/t_{CH4}	[31]
L_{km}	$5.26 \cdot 10^{11}$ km/year	Calculated from [32]
$L_{km/CH4}$	28.2 km/kg_{CH4}	Calculated from [24], for cars
$L_{km/Et}$	1.6 km/MJ	Calculated from [33], for cars
$L_{km/H2}$	116 km/kg_{H2}	Calculated from [33], for hydrogen fuel cell cars
W	62.1 Mt_{DM}/year	Calculated from [34] using mid-points of the generation range of OFMSW, manure, agricultural residues and sewage sludge for the UK
$Y_{ADCH4/M}$	0.162 t_{CH4}/t_{DM}	Calculated with the assumptions on the biodegradability (80 % conversion) and yield of H_2 and CH_4 from biomass components used in [34]. For waste, composition according to [34]. For miscanthus, composition according to [35]
$Y_{ADCH4/W}$	0.200 t_{CH4}/t_{DM}	
$Y_{ADfsH2/M}$	0.012 t_{H2}/t_{DM}	
$Y_{ADfsH2/W}$	0.014 t_{H2}/t_{DM}	
$Y_{ADssCH4/M}$	0.138 t_{CH4}/t_{DM}	
$Y_{ADssCH4/W}$	0.172 t_{CH4}/t_{DM}	
$Y_{M/A}$	13 t/ha.year	Assumed from miscanthus yields [36, 37]
$Y_{SMRH2/CH4}$	0.5 t_{H2}/t_{CH4}	From stoichiometry of SMR $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$
$Y_{SMRH2O/H2}$	4.5 t_{H2O}/t_{H2}	
$Y_{WEH2O/H2}$	9 t_{H2O}/t_{H2}	From stoichiometry of WE $2H_2O \rightarrow 2H_2 + O_2$
η_{CHP}	0.40	[38]

4. Results

Table 2 shows the fuel, energy, land and water requirements for the nine scenarios.

Among the scenarios 1, 2, 6 and 7, where hydrogen is the only energy vector, scenario 1 needs the highest hydrogen (20.6 Mt/year) while the lowest requirement is for scenario 2 (14.0 Mt/year). The hydrogen requirement is lower in other scenarios where methane is also used as energy vector.

In scenario 8, there is no hydrogen requirement, but 55.1 Mt/year of methane are needed. The total energy requirement is the highest for scenarios 1 and 8 (3.38 and 3.57 EJ/year, respectively), and the lowest for scenario 9 (2.06 EJ/year). Land requirements are much higher for scenarios 1, 3 and 8 (14.1, 9.02 and 20.6 Mha) than for the other scenarios and are the lowest for scenario 9 (0.73 Mha). As far as the water requirement is concerned, the highest is for scenario 2 (126 Mt/year) while scenario 8 has no water requirement. Scenarios 3 and 9 have considerably lower water requirements (40.8 and 46.6 Mt/year, respectively) than other scenarios except 8.

AD of organic waste can potentially generate up to 6.21 Mt of hydrogen per year (scenarios 1 and 6), of which 0.87 come directly from the first stage and 5.34 come from the SMR of the methane produced in the second stage. AD of waste for methane production in a single stage process (scenarios 3, 5 ad 8) can potentially generate 12.4 Mt/year of methane. In the scenarios where miscanthus is used to supply the balance of energy for heat and transport (scenarios 1 and 8) or for heat only (scenario 3), miscanthus provides most of the hydrogen (14.38 Mt/year for scenario 1) or of the methane (17.7 and 42.7 Mt/year).

The process heat requirements are the highest in scenarios 1 and 8 (0.96 and 0.68 EJ/year, respectively). The electricity requirements are dominated by WE and are the highest for the scenarios that make more use of this process (scenarios 1 and 7).

When miscanthus is used, the land for its growth is by far the largest contribution to the total land required. For example, in scenario 1 the land for miscanthus growth (13.7 Mha) represents 98 % of the total land required (the balance being used to generate electricity). In the scenarios where miscanthus is not used (scenarios 2 and 4-7) the main land use is due to electricity generation for WE.

Water consumption is mainly due to WE in all scenarios except in scenarios 1 and 8 where WE is not used.

Table 2. Results for the nine scenarios

	Scenarios								
	1	2	3	4	5	6	7	8	9
Summary of main requirements (total)									
H_2 (Mt/year)	20.6	14.0	4.53	10.6	11.5	15.4	14.3	-	6.05
CH_4 (Mt/year)	-	-	30.1	10.7	12.4	-	-	55.1	10.7
Energy (EJ/year)	3.38	2.79	2.81	2.74	2.65	2.72	2.68	3.57	2.06
Electricity (EJ/year)	0.46	2.79	1.14	1.92	1.96	1.84	2.56	0.51	1.34
Energy from waste (EJ/year)	0.88	-	0.69	0.72	0.69	0.88	0.12	0.69	0.72
Energy from Miscanthus (EJ/year)	2.04	-	0.98	-	-	-	-	2.37	-
Land (Mha)	14.1	1.52	9.02	1.04	1.07	1.00	1.39	20.6	0.73
Water (Mt/year)	79.2	126	40.8	87.4	104	107	121	-	46.6
Hydrogen, methane, miscanthus requirements (Mt/year)									
H_2 from waste first stage	0.87	-	-	0.87	-	0.87	0.87	-	0.87
CH_4 from waste second stage	10.7	-	-	10.7	-	10.7	-	-	10.7
CH_4 from waste single stage	-	-	12.4	-	12.4	-	-	12.4	-
H_2 from SMR	5.34	-	-	-	-	5.34	-	-	-
Total H_2 from waste	6.21	-	-	-	-	6.21	0.87	-	0.87
H_2 from miscanthus	14.38	-	-	-	-	-	-	-	-
CH_4 from miscanthus	-	-	17.7	-	-	-	-	42.7	-
Miscanthus	178	-	109	-	-	-	-	264	-
Heat requirements (EJ/year)									
AD	0.27	-	0.17	0.06	0.06	0.06	0.03	0.32	0.06
Miscanthus growth	0.09	-	0.06	-	-	-	-	0.14	-
SMR	0.34	-		-	-	0.09	-	-	-
CO_2 removal	0.25		0.12	0.05	-	0.08	0.01	0.22	0.05
Total process heat	0.96	-	0.35	0.12	0.06	0.23	0.04	0.68	0.12
Electricity requirements (EJ/year)									
AD	0.24	-	0.17	0.06	0.06	0.06	0.03	0.32	0.06
Miscanthus growth	0.08	-	0.05	-	-	-	-	0.12	-
SMR	0.02	-	-	-	-	0.01	-	-	-
CO_2 removal	0.04	-	0.02	0.01	-	0.01	<0.01	0.04	0.01
WE		2.55	0.83	1.77	2.10	1.68	2.45	-	0.94
H_2 compression	0.08	0.24	0.08	0.08	0.08	0.08	0.08	-	
CH_4 compression	-	-	-	-	-	-	-	0.02	

Table 2. Results for the nine scenarios

	Scenarios								
	1	2	3	4	5	6	7	8	9
				Land requirements (Mha)					
Miscanthus growth	13.7	-	8.40	-	-	-	-	20.3	-
Electricity for AD	0.13	-	0.09	0.03	0.03	0.03	0.02	0.18	0.03
Electricity for Miscanthus growth	0.04	-	0.03	-	-	-	-	0.07	-
Electricity for CO_2 removal	0.02	-	0.01	<0.01		0.01	<0.01	0.02	<0.01
Electricity for SMR	0.01	-	-	-	-	<0.01	-	-	-
Electricity for WE		1.39	0.45	0.96	1.14	0.91	1.33	-	0.51
Electricity for hydrogen compression	0.04	0.13	0.04	0.04	0.04	0.04	0.04	-	-
Electricity for methane compression	-	-	-	-	-	-	-	0.01	-
Electricity for electric vehicles	-	-	-	-	-	-	-	-	0.18
				Water requirements (Mt/year)					
For SMR	79.2	-	-	-	-	24.0	-	-	-
For WE	-	126	40.8	87.4	104	83.0	121	-	46.6

5. Discussion

5.1. Land requirements

Using miscanthus as AD feedstock, together with organic waste, needs too much land to provide all the required energy for heating and transport (scenarios 1 and 8) and/or for heating only (scenario 3). The total land in the UK is approximately 24.3 Mha, and scenarios 1, 3 and 8 would require between 38 and 85 % of the total land in the country to be used for energy generation, which is clearly impossible. Therefore scenarios 1, 3 and 8 are unfeasible.

On the other hand, when WE is used to generate the required hydrogen for heat and transport, the land requirements are much lower and feasible. For example, the land requirement for scenario 2 (WE used to provide all the heat and transport energy) is 1.52 Mha which is only 6 % of the total land of the country and much lower than for scenario 1. The land requirements in the scenarios with WE can be reduced if energy is also obtained from the AD of organic waste. For example, scenarios 4, 5 and 6 differ from scenario 2 in that part of the energy in these scenarios is obtained from waste. Due to the energy from waste, the land requirements for Scenarios 4, 5 and 6 are in the range of 1.00-1.07 Mha which is 30-34 % lower than for Scenario 2. Obtaining energy (in the form of hydrogen or methane) from AD of waste reduces the amount of hydrogen to be obtained from WE, which in turns reduces the electricity requirements and the land required to generate electricity with solar panels. In scenarios 4-6, the energy generated from waste corresponds to 26-32 % of the total energy required. In Scenario 7 the contribution of energy from waste is lower than in other scenarios because only the first stage of AD is used for energy generation. However, an advantage of scenario 7 is that the digestate from AD can still be valorised to produce chemicals, which is not possible in scenarios 4-6 where most of the organic matter is converted into energy. From the land requirements point of view, scenario 9 is the best one as it needs only 0.73 Mha which is 3 % of the total land in the UK and at least 27 % less than in any other scenarios. The reason for the lower land requirement in scenario 9 is the direct use of electricity for transport. Electric vehicles are more energy efficient than other types of vehicles and this corresponds in a lower land required to generate the required electricity.

5.2. Water requirements

As far as the water requirements are concerned, the scenarios that make more use of WE are the ones with the highest requirements. The annual consumption of drinking-quality water in the UK can be estimated at approximately 3,400 Mt/year [39], therefore the highest water consumption calculated in this study (126 Mt/year for Scenario 2) corresponds to an increase of 3.7 % in the drinking water supply in the country. Although this increase is not insignificant, it is relatively minor considering that an additional capacity of approximately 1,200 Mt/y in the water system in the country is required by 2050 [39]. The water required for energy generation can be reduced by making use of energy from waste. Scenarios 4, 5 and 6 give a reduction in water requirements between 14 and 30 % compared to scenario 2 where no energy from waste is used. The scenarios based on AD of miscanthus (scenarios 1, 3 and 8) have lower water requirements than the scenarios based on WE, however these scenarios are unfeasible due to the too high land requirements. Scenario 9, based on the use of electric vehicles, is particularly attractive also due to its low water consumption, which is in turn due to the direct use of electricity for transport. It is however important to observe that the calculations reported in this study only refer to the direct water consumption due to the chemical reactions of WE and SMR. In a full life cycle assessment, which is outside the aim of this study, the indirect water consumption by the considered processes should also be factored in.

5.3. Sensitivity analysis

The sensitivity of the required land to the values of some of the parameters used is shown in Figure 2. Figure 2a considers the scenarios with miscanthus, as a function of the miscanthus harvest yield. A maximum yield of 40 t/ha.year is assumed, based on the literature [40]. For the highest yield, the required land decreases considerably to 4.69, 3.35 and 6.87 Mha for scenarios 1, 3 and 8, respectively, representing a decrease of 65-70 % compared to the base cases (miscanthus yield of 13 t/ha.year). However, even under these optimistic assumptions on the yield, the land required in the scenarios with miscanthus is still considerably higher than in the scenarios based on WE (land requirements of 1.52 Mha or lower). Furthermore, high yields of energy crops are usually reported for controlled sites under optimum conditions and are difficult to achieve under commercial full-scale conditions [40]. It is important to observe that our study assumes a constant yield, while the biomass yield per unit land depends on the characteristics of the land (e.g. type of soil, moisture, temperature). By comparison, a spatial distribution of the potential yields of cassava and sweet sorghum was obtained for five provinces in China, obtaining biomass yields in the wide range 0.07-60 t/ha.year, with an average value of approximately 30 t/ha.year [13]. Since the scenarios with miscanthus require much larger areas than the other scenarios, in the rest of the sensitivity analysis (Figures 2b)-f)) the scenarios with miscanthus are excluded, in order to focus our analysis on the more interesting scenarios based on WE.

Figure 2b shows the effect of the conversion of the organic waste in the AD process. Increasing the conversion yield from 65 % to 95 % (lowest and highest values assumed, the base case assumes 80 % conversion) reduces the required land by a factor 15-22 % in scenarios 4, 5, 6 and 9. The highest benefit is observed for scenario 9 (with a land requirement of 0.66 Mha for conversion efficiency of 95 %) as in this scenario energy from waste represents a higher contribution to the total energy.

Figure 3c shows the effect of not including the heat requirements of the AD process. The base case assumes that the AD process requires heating to be maintained at the optimum temperature, however AD can be operated also at lower temperatures and in principle without any external heating energy [41]. Excluding the AD heat requirements gives a reduction of up to 5 % in the total land required, which is for scenario 9 where the land required is reduced to 0.69 Mha.

Figure 2d shows the effect of the solar PV capacity per unit of land area. An analysis of ten solar PV farms in the UK showed that the installed capacity per unit area varies in the range 41-86 MW/km^2 (our base case assumes 54 MW/km^2) [21]. Increasing the solar panel capacity from 41 MW/km^2 to 68 MW/km^2, maintaining the load factor at 0.1076, reduces the land required by approximately 40 % in all scenarios. For the highest capacity, the land required for scenarios 4, 5 and 6 is in the range 0.80-0.85 Mha and for scenario 9 is 0.58 Mha.

Figure 2e considers the effect of the energy use of WE. The lowest WE energy use of 145,618 MJ/t_{H2} gives a reduction of 31-33 % in the land required compared to the highest energy use of 218,426 MJ/tH_2 for scenarios 2, 4, 5, 6 and 7 and of 25 % for scenario 9.

The lowest WE energy use gives a land requirement of 0.63 Mha for scenario 9 and of 0.82-0.85 Mha for scenarios 4-6.

Figure 6f shows the effect of hydrogen mileage for the scenarios with hydrogen for transport. Increasing the hydrogen mileage from 93 km/kg to 138 km/kg give a reduction in the land required in the range 12-17 % for Scenarios 2, 4, 5, 6 and 7. For scenarios 4-6 the highest hydrogen mileage corresponds to a land requirement in the range 0.92-0.96 Mha. Scenario 9 is unaffected by the hydrogen mileage as it doesn’t use hydrogen for transport.

5.4. Comparison with literature

Although studies directly comparable to the present one are not reported in the literature, our results qualitatively agree with the main findings of other papers. In a study focused on the USA and only considering transport energy with bioethanol from corn [42], the authors concluded that growing corn on the available land would be enough to ensure 10 % v/v ethanol fraction in all the gasoline used in the country, but not much more, concluding that there was not enough land to supply a large fraction of the transport energy. The authors also observed that much more energy is generated per unit land with solar PV panels integrated with WE for hydrogen production than by growing biomass. In another study which included the USA, Canada, the European Union, China and Russia, the authors concluded that corn-based ethanol was not a feasible option to replace fossil fuels because of the too large land requirements [43]. The land requirement for energy generation per person (without distinction between electricity, heating energy and fuels) was found to be much higher (by a factor of 30 or higher) for energy from biomass than for solar PV panels [10]. The results of the cited study, if applied to calculate the land requirement for the total (electricity, heating and fuels) energy supply in the UK with solar PV panels, give a solar PV land requirement of approximately 1.7 Mha, in general good agreement with the present study. A comparison of the land requirements for electricity generation with solar PV panels, wind, biomass or hydroelectric turbines found that solar PV panels require the least area of land and biomass requires the largest [11]. A recent study showed that solar-powered electric cars have the smallest land requirements, followed by solar-powered hydrogen cars, while biofuel-powered cars have the largest land requirement [12]. The cited study calculates lower land requirements for transport energy than our study (0.00091 vs 0.0021 m^2/km for solar-powered electric vehicles and 0.0023 vs 0.0093 m^2/km for solar-powered hydrogen cars). This difference is due to the different assumptions on the energy generated by PV panels per unit land (the cited study uses global average values of the solar irradiation while we used values for the UK), on the efficiency of WE and on the mileage of electric or hydrogen cars per unit of energy.

5.5. General remarks

In summary, our study indicates that, in terms of minimising the land requirements for renewable energy generation, the best scenarios are those based on hydrogen fuel cell vehicles or electric vehicles. Energy generation from waste via anaerobic digestion is beneficial and can have a significant impact in reducing the land requirements. For these scenarios, the supply of all the required energy for domestic heating and transport would require a large but probably feasible land area. On the other hand, the use of land to grow energy crops is not recommended to supply the bulk energy requirements as the land requirements would be too large. However, energy crops for AD can still be beneficial in some cases, e.g. where the land is suitable for crops growth but not for other renewable energy installations or to supply energy when the electricity grid is at its maximum capacity.

In addition to the calculations on the land and water requirements done in this paper, many other considerations, outside the scope of this paper, need to be done to evaluate the feasibility and sustainability of the different scenarios for renewable heating and transport energy. The sustainability of anaerobic digestion can be improved by technological innovations, e.g. high-pressure digestion that can increase the purity of methane in the biogas, reducing the energy and costs associated with carbon dioxide removal and with the injection of biogas into the gas grid [44]. Similarly, alternative technologies such as photoelectrochemical water splitting or anion exchange membrane water electrolysis can potentially improve the sustainability of renewable hydrogen generation from water, although these processes are still at the research stage [45, 46]. Safety of hydrogen production, distribution, storage and combustion needs to be considered before hydrogen is fully deployed as energy vector [47]. This study assumes electricity generation by onshore PV panels, but offshore wind can potentially supply part of or all the required electricity, therefore reducing the onshore land requirements. For example, it has been estimated that potentially 20 EJ/year of electricity could be generated from offshore wind turbines at a cost of up to 140 £/MWh, using 37 % of the REZ (renewable energy zone) for wind energy deployment [48]. Although other more conservative estimates indicate that the offshore wind electricity potentially achievable in the UK by 2030 is in the order of 0.5 EJ/y [49], there is clear indication that offshore wind could potentially provide all or a significant part of the electricity requirements calculated in this study. Indirect water requirements, e.g. water used in the production of solar panels, should also be considered. Energy storage, density and autonomy of vehicles are also important factors that need to be considered in the choice of the best technology. Finally, life cycle assessment and cost analysis of any scenarios are critical elements which need to be evaluated to fully understand the feasibility and sustainability of renewable energy generation. A life cycle assessment for California [50] has shown that the carbon dioxide emissions of hydrogen fuel cell vehicles are about half of the conventional internal combustion engines if hydrogen is produced from water electrolysis using renewable electricity from solar PV panels or wind turbines. Currently, the cost of hydrogen from WE is not yet competitive with hydrogen from fossil fuels (cost estimations give \$5.5/kg_{H2} vs \$1.39/kg_{H2} from WE and fossil fuels, respectively) [51]. The cost of electricity generation from AD has been estimated as low as £0.019/kWh_e for large plants [52]. The cost of battery electric vehicles has been decreasing in recent years and is close to becoming competitive with more conventional petrol and diesel vehicle [53]. Ultimately, cost is the determining factor in the success of renewable energy technologies, as shown by the analysis of consumer surveys [54].

As far as the practical implications of this study are concerned, we can summarise them as follows: 1) technology development should be more focused on electric or hydrogen fuel cell vehicles than on using energy crops; 2) technology developments in energy from waste should be encouraged as they can reduce the land requirements for renewable energy generation; 3) technology developments for hydrogen boilers should also be encouraged, as hydrogen could provide all the heating energy required in the UK from renewable resources; 4) the use of hydrogen (from WE)-methane (from AD) mixtures for heating should be investigated; and 5) the generation of renewable electricity from solar

PV panels should be incentivised, as it could provide all or most of the energy required in the UK for transport and heating.

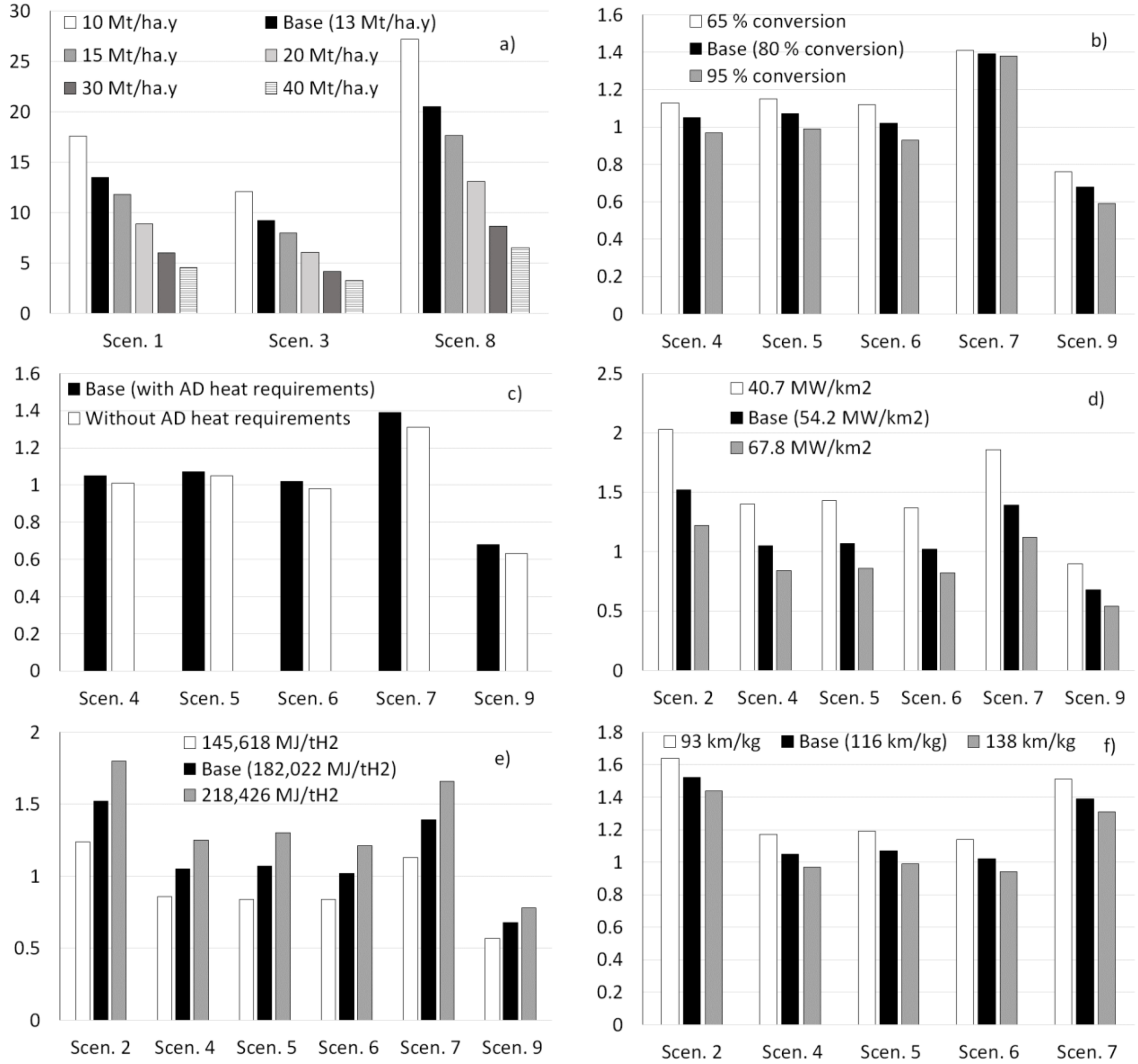

Figure 2. Sensitivity analysis on the land requirements. In all figures the y-axis shows the land required in Mha. a) Miscanthus yield; b) Conversion of organic matter; c) AD heat requirements; d) solar PV capacity per unit land; e) energy required for WE; f) distance travelled by hydrogen cars.

Conclusions

Nine different scenarios are considered for the generation of renewable energy for domestic heating and road transport in the UK and the required land and water are calculated for each scenario. The land required to supply the energy for the conversion processes is also considered. AD of organic waste and of energy crops is considered for hydrogen and/or methane production while WE is used for hydrogen production. In addition, battery electric vehicles are also considered. The required electricity is assumed to be generated by solar PV panels. Scenarios based on energy crops give much higher land requirements than scenarios based on WE and are therefore not recommended. The lowest land requirement (0.73 Mha, about 3 % of the total UK land) is obtained with the use of battery electric vehicles for transport and of a combination of WE and AD of waste for heating. For the scenarios which use hydrogen fuel cell vehicles for transport, the lowest land requirements (1.00-1.07 Mha, about 4 % of the total UK land) are obtained by combining WE and AD of organic waste.

The direct water requirement for the considered processes in the most promising scenarios correspond to an increase of 1-4 % of the water (drinking quality) requirement of the country and are likely to be achievable.

Overall, this study shows that the land and water requirements to supply all the energy used in the UK for domestic heating and road transport are likely to be acceptable, also considering that the land requirement can be reduced by making more use of offshore energy.

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