Electronic Supplementary Material (ESI) for Sustainable Energy & Fuels.

Electrofuels from excess renewable electricity at high variable renewable shares: cost, greenhouse gas abatement, carbon use and competition

Supplementary Material

Table 1 Feedstock fit to the processes, including biomass specific conversion efficiencies. The energetic biofuel output per input of the main biomass feedstock is stated according to $\eta_{low}{=}\dot{e}_{out,main}\ \dot{e}_{in,main}^{-1}$, why above unity is possible through the addition of hydrogen as a secondary feedstock. The assumed maximum potential for biofuel production in this paper is stated, not the overall potential. Wood residues are here assumed to be used in other sectors, such as e.g. for heating, chemicals and materials. The crop prices were calculated based on Millinger and Thrän [1].

Fuel	**CH_4/SNG**	**EtOH**	**MeOH**	**FAME**	**HVO**	**FT**	**PBtL**	**PBME**		
Crops										
Rape seed				0.59-0.62	0.6					
Maize silage	0.56-0.7							1.12-1.4		
Grains		0.48-0.53								
Short rotation coppice (poplar)	0.58-0.73	0.3-0.45	0.42			0.35-0.45	1.05-1.35			
Sugar beet	0.56-0.7	0.53-0.58								
Residues									**PJ**	**€ GJ^{-1} 2020**
Straw	0.5	0.3-0.45						1-1.2	57	12.8-16.9
Manure/slurry	1							2	83	0
Used cooking oil				0.93-0.96	0.94-0.96				14	16
Household biowaste	0.82-0.86							1.64	10	0

Table 2 Input data for cultivation of included biomass crops.

		Rape Seed	Maize Silage	Wheat	Poplar	Sugar Beet
Dry matter (DM) content	frac	0.91	0.35	0.86	0.45	0.23
Energy density,DM	GJ tDM^{-1}	26.5	17	17	17.6	17
Yield,fresh matter (FM)	tFM ha^{-1}	3.5	45-55	7.9	18-27	65
Labour	h ha^{-1}	5.5	10.8	5.4	0.3	7.8
Diesel	l ha^{-1}	73	112	73	2.1	111
Machine cost,fix	€ ha^{-1}	176	292	164	5.4	318
Machine cost,variable	€ ha^{-1}	148	248	146	7.1	291
Service cost	€ ha^{-1}	0	0	0	564	0
Direct cost	€ ha^{-1}	520	406	508	87	600
Arable land use 2017	ha	798300	891300	404500	6000	46400
Seeds	kg $(ha \cdot a)^{-1}$	6	25	120	0	6
N_2O (incl. N_2O field emissions)	kgN_2O $(ha \cdot a)^{-1}$	3.1	4.66	1.81	1.28	3.27
N	kg $(ha \cdot a)^{-1}$	137.4	63.2	109.3	0	119.7
Diesel	l $(ha \cdot a)^{-1}$	73	112	73	2.1	111
Seeds Emission Factor	kgCO_2eq kg^{-1}	0.73	0.32	0.81	0	3.54

Table 3 Process data of renewable fuel process options included. The Full-load hours (FLH) of PtG-H2 are set endogenously within the model.

		BME	BeetEtOH	StarchEtOH	FAME	HVO	SNG	LignoEtOH	LignoMeOH	FT	PBtL	PBME	LCH4	PtG-H2	FCEV	PtG-CH4	PtL
Life-time	a	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
FLH,low	h a^{-1}	8000	8000	8000	8000	8000	8000	8000	8000	8000	8000	8000	8000		6500	8000	8000
FLH,high		8000	8000	8000	8000	8000	8000	8000	8000	8000	8000	8000	8000		7000	8000	8000
Invest,high	€ $kWcap^{-1}$	1700	1390	1390	245	780	1500	3060	918	2500	3000	2040	550	1500	4000	2000	2000
Invest,low		1700	1390	1390	245	500	1800	2907	800	2300	2500	2040	550	800	2300	1500	1500
Cap,start	PJ_{cap}	35	4	16	98	0	0	0	0	0	0	0	0	0	0	0	0
O&M	% of Invest	5.9	6.6	5.3	7.8	4.6	4.2	3.7	4	4.4	2.5	3.3	3.7	4	1	4	4
Personnel	€ GJ^{-1}	0.7	0.6	0.32	0.3	0.21	1.0	1.1	0.6	0.6	0.6	0.6	0.3	0.238	0.0	0.5	0.5
Efficiency η_{low}	$\dot{e}_{out,1}\ \dot{e}_{in,1}^{-1}$										1.05	1.12	0.98	0.65	1.00	0.91	0.69
Efficiency η_{high}	$\dot{e}_{out,1}\ \dot{e}_{in,1}^{-1}$										1.35	1.4	0.98	0.7	1.00	0.91	0.69
$Heat_{in}$	kWh GJ^{-1}	30	100	125	34.8	4.2	0	197	0	0	0	13.9	0	0	0	0	0
$Electricity_{in}$	kWh GJ^{-1}	22	30	17.3	3.1	2.9	28	38	24.7	69	36.1	30.6	12	0	0	0	0
$Methanol_{in}$	t GJ^{-1}				0.0033												
$H_{2,in}$	GJ GJ^{-1}					0					0.87	0.56			1.00	1.2	1.17
$CO_{2,in}$	t GJ^{-1}															0.055	0.071
$Digestate_{out}$	tDM GJ^{-1}	0.295										0.295					
$Vinasse_{out}$	tDM GJ^{-1}		0.0237					0.05									
$Dried\ Pulp_{out}$	tDM GJ^{-1}		0.0248														
$Aldehyde_{out}$	tDM GJ^{-1}		0.0007														
$DDGS_{out}$	tDM GJ^{-1}			0.04443													
$Schrot_{out}$	tDM GJ^{-1}				0.0325												
$Pharmaglycerin_{out}$	tDM GJ^{-1}				0.0025												
$Naphtha_{out}$	tDM GJ^{-1}					0.0017				0.0084							0.0058
$Lignin_{out}$	tDM GJ^{-1}							0.07									
$Biopropane_{out}$	tDM GJ^{-1}					0.0015											

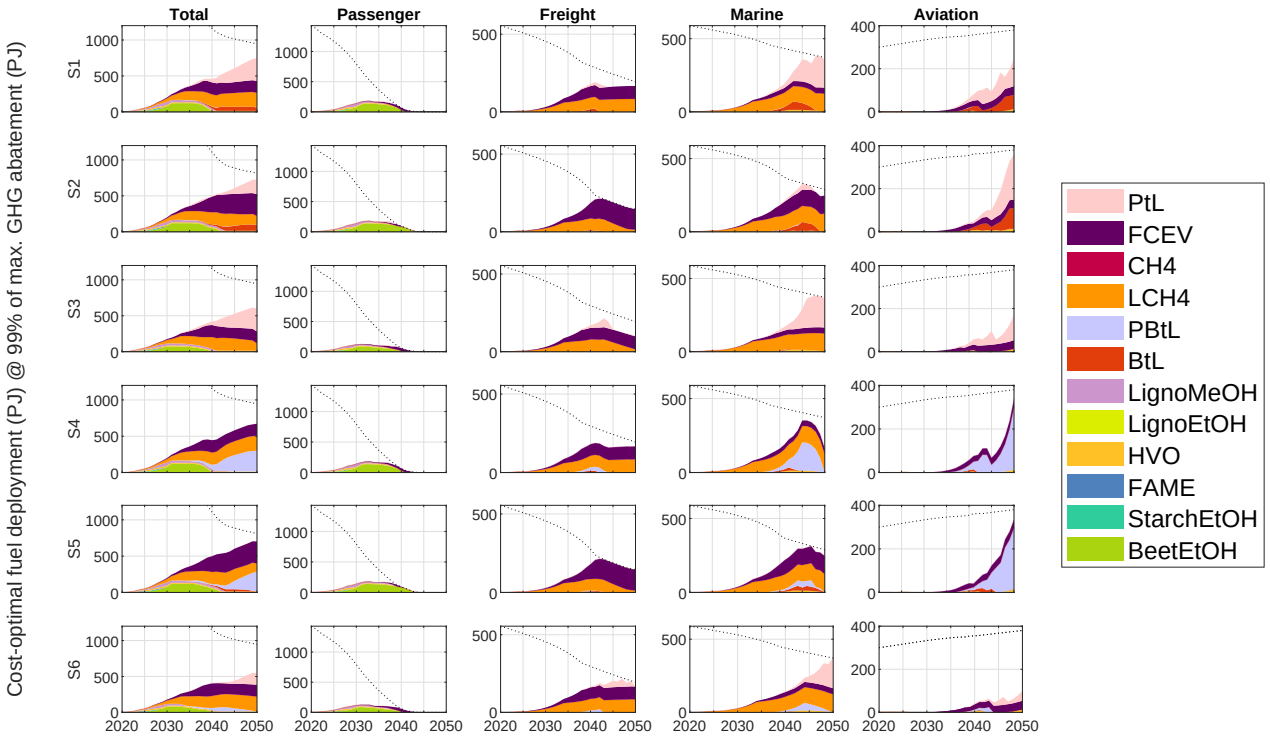

Fig. 1 Cost-optimal fuel deployment at 99% of the maximum GHG abatement in the scenarios. Abbreviations: PtL=Power-to-Liquid, FCEV=Fuel-cell electric vehicle (with hydrogen as fuel), CH_4=methane, LCH_4=Liquefied methane, PBtL=Power-plus-Biomass-to-Liquid, BtL=Biomass-to-Liquid, LignoMeOH=Lignocellulose-based methanol, LignoEtOH=Lignocellulose-based ethanol, HVO=Hydrotreated vegetable oil, FAME=Fatty-acid methyl ester, StarchEtOH=Starch-based ethanol, BeetEtOH=Sugar beet based ethanol. The areas show the deployment in Petajoule (PJ) of the different options over time, and the dotted line shows the total fuel demand. The demands differ between scenarios due to differing fuel economies of the deployed fuels, while keeping the transport service constant across scenarios.

Notes and references

1 Markus Millinger and Daniela Thrän. Biomass price developments inhibit biofuel investments and research in Germany: The crucial future role of high yields. *Journal of Cleaner Production*, 172:1654–1663, 2018. ISSN 09596526. doi: \url{10.1016/j.jclepro.2016.11.175}.