

Appendix

A modelling framework for assessing the impact of green mobility technologies on energy systems

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Abstract:

A successful decarbonisation of the European Union, coupled with a high integration of renewable energy and ambitious targets for energy efficiency, can only be reached with a significant contribution from the transportation sector. It currently represents a quarter of the total greenhouse gas emissions and is shifting from fossil fuels to alternative energy carriers (biofuels, e-hydrogen, electricity) and propulsion systems (hybrid, electric and fuel-cell vehicles). Decarbonising this sector can follow multiple pathways, each having different costs, impacts and implications for the other sectors (industry, residential and services). This paper presents a method to analyse the impact of each decarbonisation pathway in the mobility sector on the overall energy system, using the EnergyScope model. The proposed methods include: (i) an estimation of the hourly demand profiles for short- (local) and long-distance mobility, using annual projections and traffic measurements; (ii) the development of black-box vehicle models of road, rail and aviation technologies; (iii) the modelling of the associated infrastructures, from the fuel conversion processes to the charging stations; and (iv) the use of Monte-Carlo-based tools to account for technical and economic uncertainties. This method allows to assess the effects of mobility decarbonisation pathways on the energy system, from the large-scale deployment of vehicle-to-grid technologies to the integration of biofuel- and hydrogen-based vehicles. France has been taken as case study, considering 2050 as time horizon. The results showed the importance of a holistic approach to suggest cost- and energy-efficient decarbonisation pathways in the transport sector that can affect the overall energy system.

Keywords:

Energy system; Mobility; Decarbonisation

Appendix 1: Model comparison

Table A1: Comparison of existing large scale energy planning models from Limpens et al. with mobility specific modelling and Mobility EnergyScope as comparison

Model	Mobility	Multisector	Open Source	Optimisation	Comp. time.
Calliope	✓	✓	✓	✓	minutes
COMPOSE	✗	✓	✗	✓	-
DESSTinEE	✓	✓	✓	✗	seconds
DIETER	✓	✗	✓	✓	minutes
EnergyPLAN	✓	✓	✗	Operations only	seconds
MARKAL/TIMES	✓	✓	✗	Investment only	5-35 minutes
Oemof	✓	✓	✓	✓	minutes
OSemMOSYS	✓	✓	✓	✓	minutes
PyPSA	✓	✓	✓	✓	minutes
STREAM	✓	✓	✗	✗	-
Switch	✓	✗	✓	✓	10-20 minutes
URBS	✗	✗	✓	✓	60 minutes
EnergyScope Monthly	✓	✓	✓	✓	seconds
EnergyScope TD	✓	✓	✓	✓	1 minute
MobES Monthly	✓	✓	✓	✓	seconds
MobES TD	✓	✓	✓	✓	3-10 minutes

Appendix 2: Mobility Modelling framework

General framework

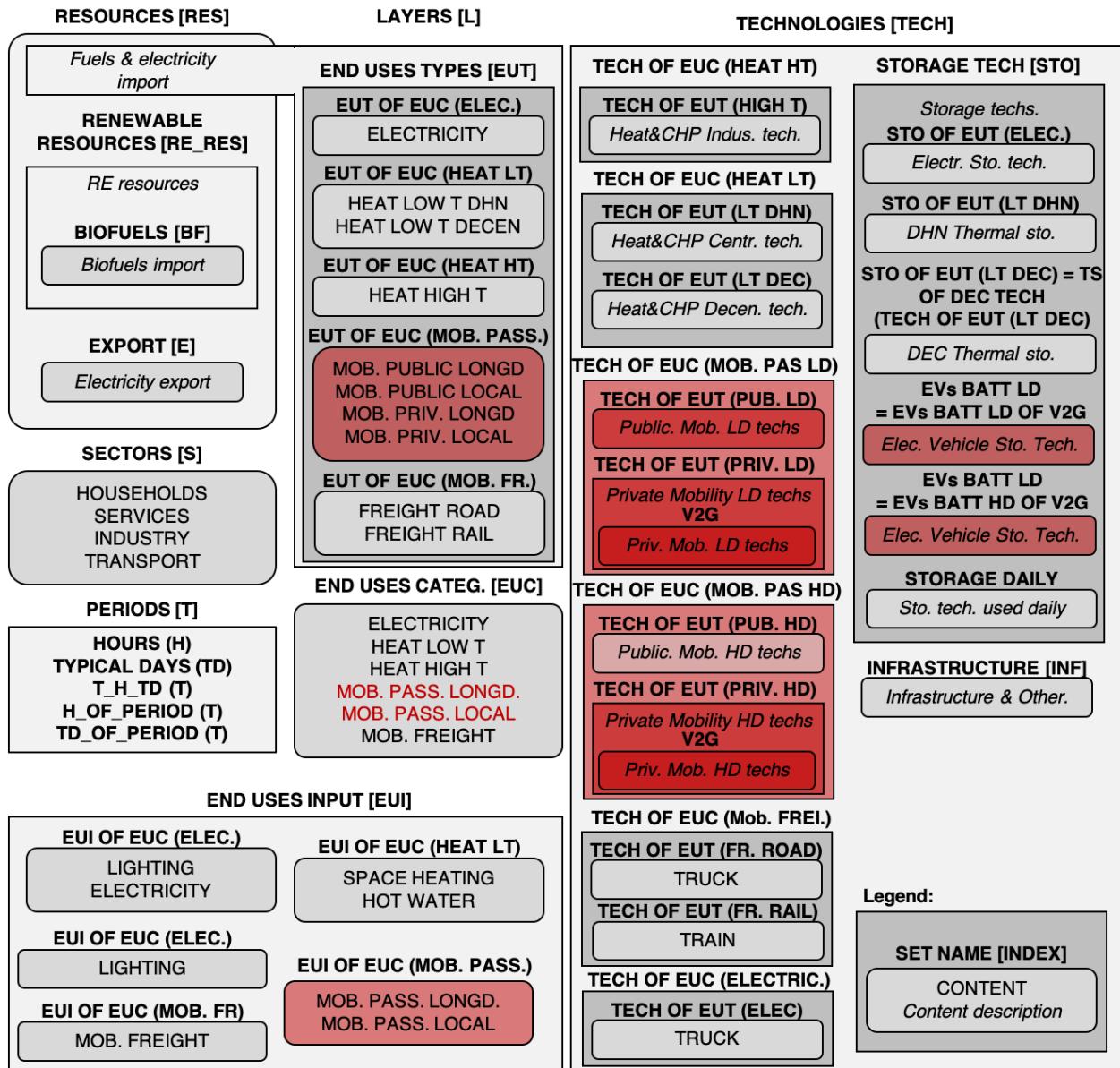


Figure A1: Graphic representation of the sets and indices of the MILP framework. Abbreviations: space heating (SH), hot water (HW), temperature (T), mobility (MOB), vehicle-to-grid (V2G), thermal storage (TS), low distance (LD) and high distance (HD). Red entries are the modifications done on Limpens.

End Use demands

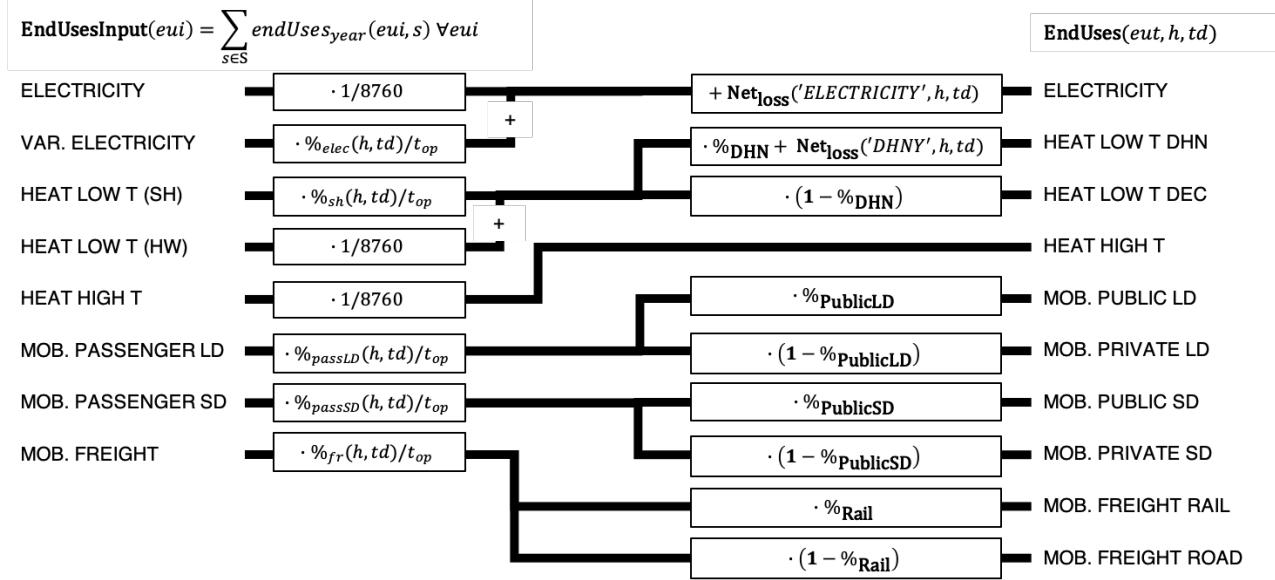


Figure A2: End-uses calculation starting from yearly demand model inputs ($endUsesInput$). Adapted from Limpens et al. Abbreviations: space heating (sh), district heating network (DHN), hot water (HW), passenger long distance (passLD), passenger short distance (passSD) and freight (fr).

Technologies

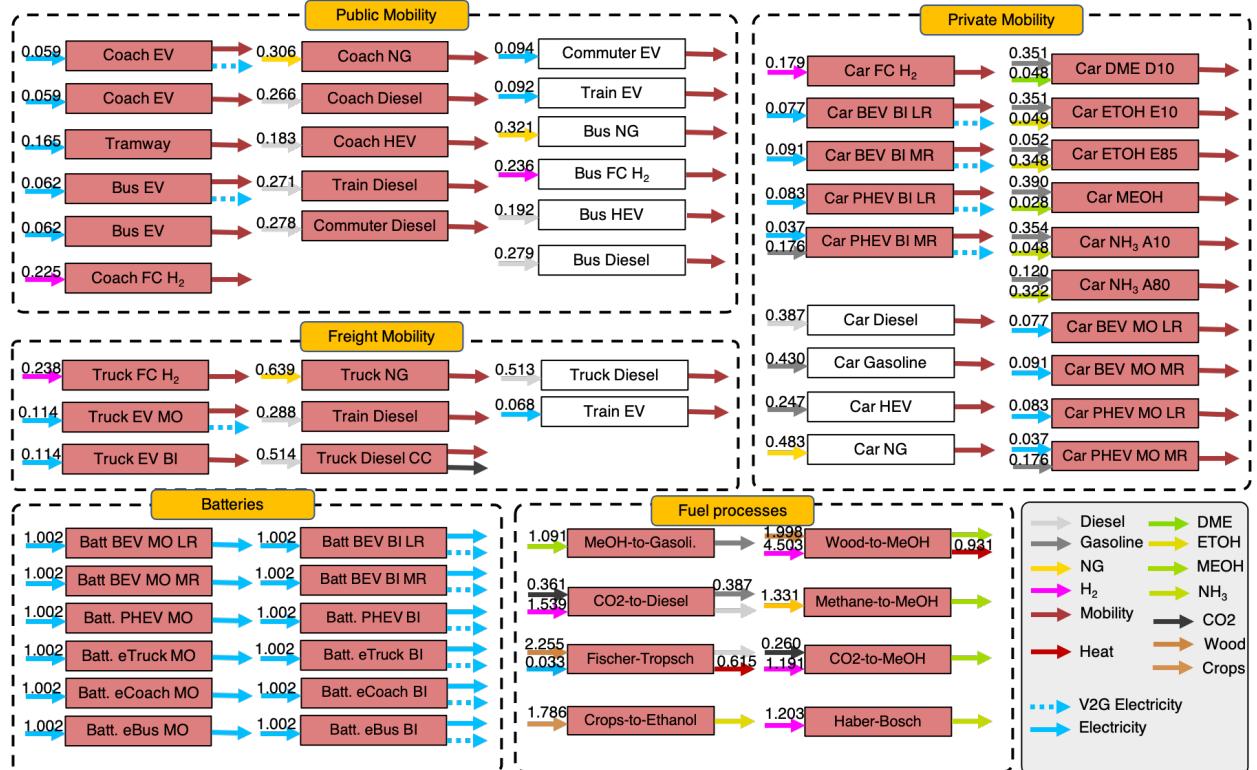


Figure A3: Application of the LP modelling framework to the European energy system with efficiencies to produce 1 unit of output (Public & Private mobility [pkm], freight mobility [tkm], others [Wh]).

Additional technologies to Limpens Figure 5. White boxes represent existing technologies, while red boxes are the additional technologies

Vehicle & Infrastructure characterisation parameter determination

Table A2: Normalized costs private mobility vehicles by country

	c _{inv} ²⁰²⁰ [CHF/car]	c _{inv} ²⁰²⁰ [CHF/pkm/h]		c _{inv} ²⁰⁵⁰ [CHF/pkm/h]		c _{maint} [CHF/pkm/h/y]	
		Germany	France	Germany	France	Germany	France
BEV LR	28'190	616.1	585.7	188.51	179.2	10.6	10.1
BEV MR	64'210	1403.3	1334.0	429.2	408.0	10.6	10.1
(P)HEV	67'660	1478.7	1405.7	1196.1	1137.0	36.2	34.4
NG	25'420	555.5	528.1	-	-	25.6	24.4
Gasoline	32'000	699.4	664.8	-	-	25.6	24.4
Diesel	29'500	644.7	612.9	-	-	25.6	24.4
Fuel Cell	70'000	1529.8	1545.3	612.3	582.0	25.6	24.4
VFF	32'500	710.3	675.2	-	-	10.6	10.1

Table A3: Global warming potential private mobility vehicles construction (D/F).

[kt CO ₂ ^{equ} /Mpkm/h]	GWP 2017		GWP 2017	
	Germany	France	Germany	France
BEV LR	405	385	332	316
BEV MR	779	741	585	556
PHEV	546	519	539	512
NG & Gasoline	360	342	360	342
Diesel	364	346	364	346
Fuel Cell	827	786	538	512
Other	366	348	366	348

Table A4: Normalised costs and GWP synthetic fuel processes

	c _{inv} ²⁰⁵⁰ [CHF/GW]	c _{maint} ²⁰⁵⁰ [CHF/GW]	GWP _{constr} ²⁰¹⁵ [Mt CO ₂ -eq./GW]
MeOH-to-Gasoline	1001	69	0.21
CO ₂ -to-Diesel	681	68	1.77
Fischer-Tropsch	1955	35.81	0.98
Crops-to-EtOH	2236	165.72	4.74
Wood-to-MeOH	2500	125	3.56
Methane-to-MeOH	1023	51.18	1.46
CO ₂ -to-MeOH	972	98.7	2.77
Haber-Bosch	595	30	1.03

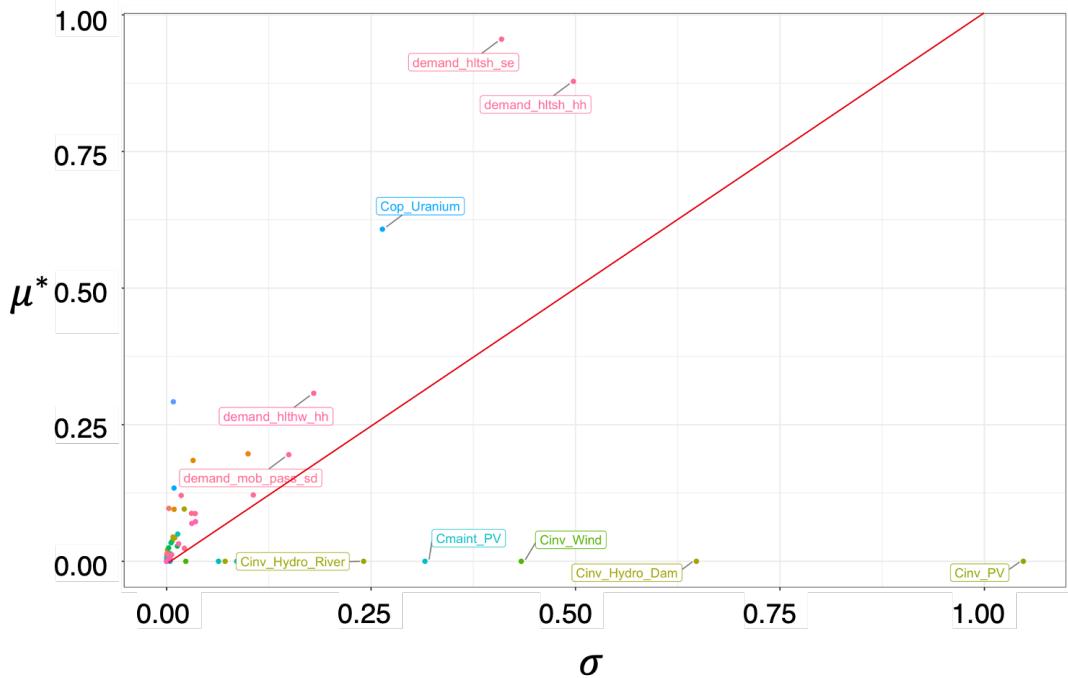
Table A5: Parameters Synthetic fuels

	HV _m [MJ/kg]	HV _{rho} [MJ/L]	ρ [kg/L]	N _C [-]	gwp _{op} [kg – CO ₂ eq/MJ]
Gasoline	43.1	32.2	0.745	0.842	0.071
Diesel	43.2	35.9	0.832	0.857	0.073
Natural Gas	42.4	33.9	0.8	0.75	0.065
Ethanol	29.7	23.4	0.789	0.522	0.064
Methanol	22.7	18.0	0.792	0.375	0.061
Hydrogen	142	1.28×10^{-2}	8.99×10^{-5}	0	0
Ammonia	22.5	13.5	0.601	0	0

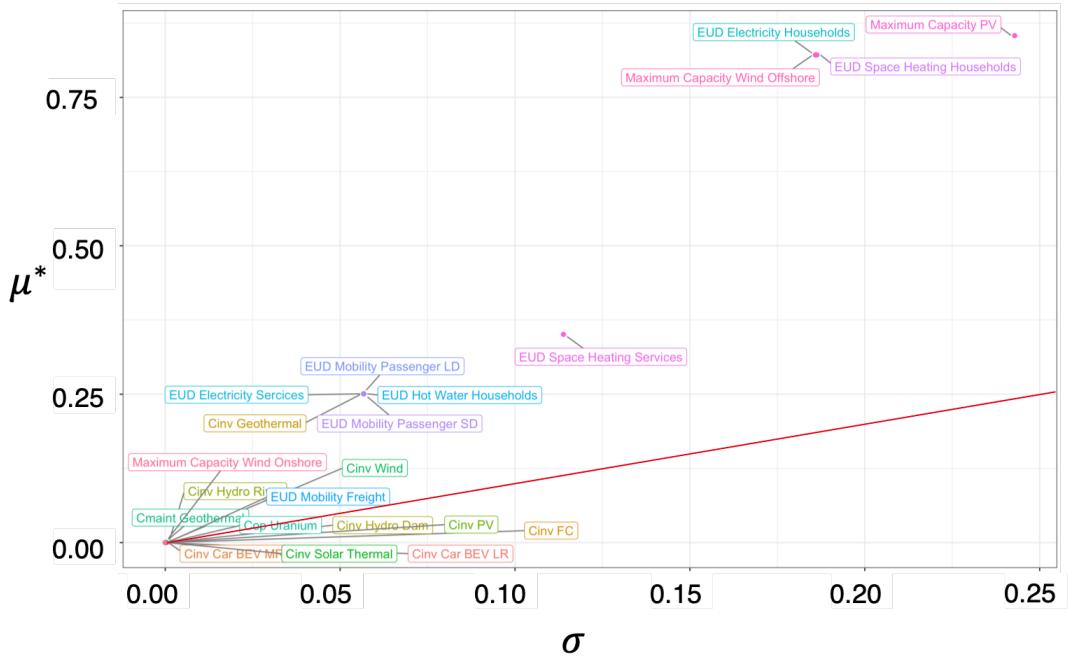
Appendix 3: Sensitivity analysis

Table A6: Morris analysis input parameters and results for 20 most influential parameters - the term "Cinv" refers to the specific investment cost of a technology, "Cop" to the cost of a given resource, "Cmaint" to the maintenance cost, "Demand" to the actual demand (in GWh for energy or pkm for mobility) and "fmax" to the maximum potential/installed capacity of renewable energies

Parameter	Min	Max	Base	μ	σ	μ^*
Cinv Car BEV LR	3.00E+03	8.00E+03	5.50E+03	7.61E-02	8.11E-03	7.61E-02
Cinv Car BEV MR	6.60E+04	2.00E+05	1.30E+05	5.12E-02	7.18E-03	5.12E-02
Cinv Car FC	7.20E+05	2.20E+06	1.50E+06	-7.57E-02	2.02E-04	7.57E-02
Cinv Dec Solar	3.80E+06	1.20E+07	7.70E+06	4.31E-05	1.60E-04	4.31E-05
Cinv DHN Geo.	8.10E+07	2.40E+08	1.60E+08	-1.43E-01	1.06E-01	1.43E-01
Cinv Hydro Dam	2.40E+09	7.20E+09	4.80E+09	1.20E-05	6.43E-01	1.20E-05
Cinv Hydro River	2.70E+10	8.10E+10	5.40E+10	3.12E-04	2.48E-01	3.12E-04
Cinv PV	5.00E+10	1.50E+11	1.00E+11	2.14E-04	1.05E+00	2.14E-04
Cinv Wind	7.40E+11	2.20E+12	1.50E+12	2.70E-04	4.31E-01	2.70E-04
Cmaint PV	2.30E+12	7.00E+12	4.70E+12	1.20E-04	3.22E-01	1.20E-04
Cop Uranium	2.10E-03	6.20E-03	4.10E-03	6.19E-01	2.70E-01	6.19E-01
Demand HLTHW HH	6.80E+15	2.00E+16	1.40E+16	-3.12E-01	1.87E-01	3.12E-01
Demand HLTHW SE	7.90E+16	2.40E+17	1.60E+17	2.88E-01	1.26E-02	2.88E-01
Demand HLTSH HH	6.90E+18	2.10E+19	1.40E+19	7.62E-01	4.90E-01	7.62E-01
Demand HLTSH IN	2.10E+18	6.40E+18	4.30E+18	1.03E-01	2.01E-01	1.03E-01
Demand HLTSH SE	5.90E+20	1.80E+21	1.20E+21	-9.17E-01	3.81E-01	9.17E-01
Demand Mob. Freight	2.00E+21	6.00E+21	4.00E+21	1.26E-01	1.28E-02	1.26E-01
Demand Mob. Pass LD	2.00E+22	6.10E+22	4.00E+22	1.25E-01	1.05E-01	1.25E-01
Demand Mob. Pass SD	5.00E+23	1.50E+24	1.00E+24	1.44E-01	1.49E-01	1.44E-01
fmax PV	1.10E+22	2.00E+22	1.50E+22	7.20E-05	1.09E-01	7.20E-05
fmax Wind Offshore	7.40E+22	1.40E+23	1.10E+23	9.30E-05	3.88E-02	9.30E-05
fmax Wind Onshore	7.50E+23	1.40E+24	1.10E+24	3.20E-05	3.71E-04	3.20E-05



(a) Total Costs



(b) Total GWP

Figure A4: Sensitivity analysis reference scenario France 2050 with Morris screening.