Supplementary Material

1. Biomass-based and CO2-to-X technologies

Table : Parameters for biomass-based and CO2-to-X technologies

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Technology** | **CAPEX (CHF/kW)** | **O&M (CHF/kW/y)** | **εchem** | **εth** | **εel** | **Ref.** |
| Anaerobic digestion | 1053 | 93.75 | 0.3 |  |  | [1]-[2] |
| Anaerobic digestion and cogeneration | 1776 | 147 |  | 0.145 | 0.1295 | [1]-[2] |
| Biogas to biomethane | 781 | 102 | 0.8395 |  | 0.072 | [3] |
| Crops to ethanol | 2236 | 156.72 | 0.56 |  |  | [4]-[5] |
| Crops to jet fuels | 2942 | 148 | 0.293 |  |  | [4]-[5] |
| CO2-to-diesel | 680.75 | 68 | 0.65 (diesel)0.252 (gasoline) |  |  | [6] |
| CO2-to-jet fuels | 971.64 | 48.6 | 0.84 |  |  | [7] |
| CO2-to-methanol | 1793.7 | 89.7 | 0.738 |  |  | [8] |
| Ethanol-to-jet fuels | 706 | 44.2 | 0.57 |  |  | [4]-[5] |
| Ethylene oxidation | 1521.5 | 76.07 | 0.466 |  |  | [9] |
| Fischer-Tropsch(gasification and fuel synthesis) | 1955 | 35.81 | 0.443 | 0.175 |  | [10] |
| Gasification to H2 | 900 | 45 | 0.578 | 0.167 |  | [11] |
| Gasification to SNG | 2930.1 | 149 | 0.74 | 0.24 |  | [12] |
| Hydrothermal gasification | 1700 | 118 | 0.423 |  | 0.04 | [13] |
| Methanation | 280 | 14 | 0.833 |  |  | [14] |
| Methanol carbonylation | 3034.39 | 151.7 | 0.484 |  |  | [15] |
| Methanol to olefins | 1570 | 78.5 | 0.325 (ethylene)0.568 (propylene) |  |  | [16] |
| Methanol to aromatics | 815 | 40.75 | 0.0135 (benzene)0.085 (toluene)0.14 (xylenes) |  |  | [17] |
| Pyrolysis | 2574 | 128.7 | 0.666 |  | 0.016 | [18] |
| Wood boiler (decentralized) | 493 | 17.28 |  | 0.85 |  | [19] |
| Wood boiler (industrial) | 123 | 2.46 |  | 0.864 |  | [19] |
| Wood cogeneration (industrial) | 1154.18 | 43.24 |  | 0.53 | 0.18 | [19] |
| Wood to methanol | 2500 | 125 | 0.48 |  |  | [20] |

1. Domestic biomass resources for Switzerland

Table 2 summarized the sustainable potential and supply costs for various biomass categories in Switzerland.

Table : Sustainable potential for biomass and corresponding supply cost [21][22]

|  |  |  |
| --- | --- | --- |
| Biomass category | Sustainable Potential (GWh) | Cost (CHF/MWh) |
| Forest wood - Hardwood | 126.1 | 13.5 |
| Forest wood - Hardwood | 1567.6 | 32.0 |
| Forest wood - Hardwood | 1842.0 | 42.5 |
| Forest wood - Hardwood | 438.7 | 53.0 |
| Forest wood - Hardwood | 263.2 | 63.0 |
| Forest wood - Hardwood | 249.8 | 73.5 |
| Forest wood - Softwood | 75.1 | 19.0 |
| Forest wood - Softwood | 809.5 | 45.5 |
| Forest wood - Softwood | 973.2 | 60.0 |
| Forest wood - Softwood | 423.2 | 74.5 |
| Forest wood - Softwood | 260.6 | 89.0 |
| Forest wood - Softwood | 259.4 | 103.5 |
| Wood from landscape maintenance | 158.3 | 17.0 |
| Wood from landscape maintenance | 186.1 | 22.9 |
| Wood from landscape maintenance | 305.6 | 23.4 |
| Wood from landscape maintenance | 175.0 | 23.4 |
| Wood from landscape maintenance | 172.2 | 25.4 |
| Wood from landscape maintenance | 336.1 | 25.7 |
| Wood residues | 876.7 | 0.0 |
| Wood residues | 1315.0 | 7.2 |
| Waste wood | 314.5 | -2.1 |
| Waste wood | 502.6 | -0.7 |
| Waste wood | 757.2 | 6.0 |
| Waste wood | 1679.4 | 6.0 |
| Animal manure | 2361.1 | 0.0 |
| Animal manure | 5111.1 | 6.0 |
| Organic fraction of household garbage | 1083.3 | -6.5 |
|  of which Paper | 844.4 | 0.0 |
| Green waste from households and landscape | 1611.1 | 15.2 |
| Commercial and industrial organic waste | 750.0 | 19.4 |
| Agricultural crop by-products | 619.4 | 24.9 |
| Agricultural crop by-products | 113.9 | 73.1 |
| Fresh sewage sludge in water treatment plant  | 977.8 | 0.0 |
| Fresh sewage sludge to incineration | 222.2 | 84.1 |

## Carbon contents and supply cost for resources

Table 3 resumed the cost and carbon contents for resources for Switzerland. The values for wood, wet biomass and plants are weighted average values by aggregating corresponding sub-categories from Table 2.

Table : Carbon contents and supply cost for resources [23][24]

|  |  |  |
| --- | --- | --- |
| **Resources** | **Cost [CHF/kWh]** | **Carbon content [kt-C/GWh]** |
| ACETIC\_ACID | 0.0548 | 0.098969072 |
| ACETONE | 0.1009 | 0.078271079 |
| BENZENE | 1.52 | 0.08272534 |
| COAL | 0.0302 | 0.086896552 |
| DIESEL | 0.14 | 0.071099408 |
| ETHANE | 0.07 | 0.06025861 |
| ETHANOL | 0.256333575 | 0.070346849 |
| ETHYLBENZENE | 2.00 | 0.079641833 |
| ETHYLENE | 0.07986 | 0.065382229 |
| GASOLINE | 0.19 | 0.070831284 |
| JETFUEL | 0.19 | 0.070916553 |
| LFO | 0.15 | 0.07331229 |
| METHANOL | 0.0723 | 0.06773708 |
| NG | 0.0348 | 0.054 |
| P-XYLENE | 0.149 | 0.079915127 |
| PE | 0.1327 | 0.070527273 |
| PET | 0.0859 | 0.093094911 |
| PHENOL | 0.11 | 0.084975248 |
| PLANT | 0.0169 | 0.102564103 |
| PP | 0.1227 | 0.080260194 |
| PROPYLENE | 0.1171 | 0.067375145 |
| PS | 0.1343 | 0.081736721 |
| PVC | 0.22 | 0.098769905 |
| STYRENE | 0.13 | 0.078636959 |
| TOLUENE | 0.07 | 0.080981461 |
| URANIUM | 0.0041 | 0 |
| WASTE | 0 | 0.147601476 |
| WET\_BIOMASS | 0.0169 | 0.102564103 |
| WOOD | 0.0932 | 0.105882353 |

## Aviation demand in Switzerland

Table 4 summarized the evolution of swiss passenger distance from 2005-2015, including international and domestic flights.

Table 4: Evolution of Swiss passenger distance [unit: bpkm] [[1]](#footnote-1) by airplane [25]

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
| 22.8 | 25.1 | 26.2 | 26.3 | 28 | 29.6 | 31.122 | 32.77 | 34.505 | 36.332 | 38.256 |

Table 5 reflects the energy consumption (kerosene equivalent) by Swiss aviation in different class and different flight distance.

Table : Energy conversion factors for short and long flights [26]

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Share [%] | Economy class [MJ/pkm] | Business class [MJ/pkm] | First class [MJ/pkm] |
| Within Europe | 93%[[2]](#footnote-2) | 1.99 | 3.12 | - |
| Out of Europe | 7% | 1.08 | 2.25 | 3.48 |

Average energy consumption of aviation: 2.1226 MJ/pkm, translated to 22.6 TWh of kerosene for Switzerland with LHV 42.8 MJ/kg.

**References**

[1] Ro, K.S., Cantrell, K., Elliott, D., Hunt, P.G. (2007). Catalytic Wet Gasification of Municipal and Animal Wastes, *Industrial & Engineering Chemistry Research*, 46(26), 8839-8845. doi: 10.1021/ie061403w.

[2] Pöschl, M., Ward, S., Owende, P. (2010). Evaluation of energy efficiency of various biogas production and utilization pathways, *Applied Energy*, 87(11), 3305-3321. doi: 10.1016/j.apenergy.2010.05.011.

[3] Witte, J., Kunz, A., Biollaz, S.M.A., Schildhauer, T. (2018). Direct catalytic methanation of biogas - Part II: Techno-economic process assessment and feasibility reflections, *Energy Conversion and Management*, 178, 26-43. doi: 10.1016/j.enconman.2018.09.079.

[4] Tao, L., Markham, J.N., Haq, Z., Biddy, M.J. (2017). Techno-economic analysis for upgrading the biomass-derived ethanol-to-jet blendstocks, *Green Chemistry*, 19, 1082-1101. doi: 10.1039/c6gc02800d.

[5] Han, J., Tao, L., Wang, M. (2017). Well-to-wake analysic of ethanol-to-jet and sugar-to-jet pathways, *Biotechnology for Biofuels*, 10:21. doi: 10.1186/s13068-017-0698-z.

[6] Dimitriou, I., García-Gutiérrez, P., Elder, R.H., Cuéllar-Franca, R.M., Azapagic, A., Allen, R.W.K. (2015). Carbon dioxide utilisation for production of transport biofuels: process and economic analysis, *Energy and Environmental Science*, 8, 1775-1789. doi: 10.1039/c4ee04117h.

[7] Willauer, H.D., Hardy, D.R., Schultz, K.R., Williams, F.W. (2012). The feasibility and current estimated capital costs of producing jet fuel at sea using carbon dioxide and hydrogen, *Journal of Renewable and Sustainable Energy*, 4, 033111. doi: 10.1063/1.4719723.

[8] Perez-Fortes, M., Schöneberger, J.C., Boulamanti, A., Tzimas, E. (2016). Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment, *Applied Energy*, 161, 718-732. doi:10.1016/j.apenergy.2015.07.067.

[9] Smejkal, Q., Linke, D., Baerns, M. (2005). Energetic and economic evaluation of the production of acetic acid via ethane oxidation, Chemical Engineering and Processing: Process Intensification, 44(4), 421-428. doi: 10.1016/j.cep.2004.06.004.

[10] Peduzzi, E. (2015). Biomass To Liquids: Thermo-Economic Analysis and Multi-Objective Optimisation, N6529. PhD thesis. École Polytechnique Fédérale de Lausanne.

[11] Müller, S. Stidl, M., Pröll, T., Rauch, R., Hofbauer, H. (2011). Hydrogen from biomass: large-scale hydrogen production based on a dual fluidized bed stea, gasification system, Biomass Conversion and Biorefineries, 1, 55:61. doi:10.1007/s13399-011-0004-4.

[12] E4Tech (2010). The Potential for bioSNG Production in the UK, Technical report

[13] Gassner, M., Vogel, F., Heyen, G., Maréchal, F. (2011). Optimal process design for the polygeneration of SNG, power and heat by hydrothermal gasification of waste biomass: Process optimisation for selected substrates, *Energy & Environmental Science*, 4, 1742. doi: 10.1039/c0ee00634c.

[14] Gorre, J., Ortloff, F., van Leeuwen, C. (2019). Production costs for synthetic methane in 2030 and 2050 of an optimized Powet-to-Gas plant with intermediate hydrogen storage, *Applied Energy*, 253. doi: 10.1016/j.apenergy.2019.113594.

[15] Smejkal, Q. Linke, D., Baerns, M. (2005). Energetic and economic evaluation of the production of acetic acid via ethane oxidation, Chemical Engineering and Processing: Process Intensification, 44(4), 421-428. doi: 10.1016/j.cep.2004.06.004.

[16] Jasper, S., El-Halwagi, M. (2015), A techno-economic comparison between two methanol-to-propylene processes, Processes, 3(3), 684-698, doi:10.3390/pr3030684.

[17] Bazzanella, A.M., Ausfelder, F. (2017), Low carbon energy and feedstock for the European chemical industry, <https://dechema.de/dechema_media/Downloads/Positionspapiere/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry-p-20002750.pdf>

[18] Shemfe, M.B., Gu, S. Ranganathan, P. (2015). Techno-economic performance analysis of biofuel production and miniature electric power generation from biomass fast pyrolysis and bio-oil upgrading, Fuel, 143, 361-372. doi: 10.1016/j.fuel/2014.11.078.

[19] Pantaleo, A.M., Giarola, S., Bauen, A., Shah, N. (2014). Integration of biomass into urban energy systems for heat and power. Part II: Sensitivity assessment of main techno-economic factors, Energy Conversion and Management 83, 362–376. doi:10.1016/j.enconman/2014.03.051.

[20] Brown, A., Waldheim, L., Landalv, I., Saddler, J., Ebadian, M., McMillan, J.D., Bonomi, A., Klein, B. (2020). Advanced Biofuels - Potential for cost reduction, IEA Report, https://www.ieabioenergy.com/wp-content/uploads/2020/02/T41\_CostReductionBiofuels-11\_02\_19-final.pdf

[21] Burg, V., Bowman, G., Erni, M., Lemm, R., & Thees, O. (2018). Analyzing the potential of domestic biomass resources for the energy transition in Switzerland. Biomass and Bioenergy, 111, 60-69. https://doi.org/10.1016/j.biombioe.2018.02.007

[22] JASM data platform: https://sccer-jasm.ch/, visited on March 20, 2020.

[23] Stadler Z, Damartzis T et al. Carbon Flows in the Energy Transition, Swiss Federal Office of Energy, 2019

[24] Moret S. Strategic energy planning under uncertainty, Ph.D thesis, No. 796. EPFL, 2017

[25] E. Taylor, M. Cornet, J. Pestiaux, P. Vermeulen, Identification of levers and levels of ambition for passenger & freight transport in Europe, EUCalc project D2.2, Climact, 2018.

[26] Mobitool, https://www.mobitool.ch/fr/, visited on March 20, 2020.

1. bpkm: billion passenger kilometers [↑](#footnote-ref-1)
2. Including 33% flights within Switzerland, 40% flights within neighboring countries, and 20% flights within other European countries [25] [↑](#footnote-ref-2)