**Appendix – Input data for the generic biomass-to-end-use chain calculation**

For the research article “Techno-economic evaluation of biomass-to-end-use chains based on densified bioenergy carriers (dBECs)” a simulation tool was created in the programming environment R for techno-economic comparison of generic biomass-to-end-use chains. The database and programming code are attached and the description of the data outlined in this appendix. Monetary values for the year 2017 have been derived from statistics or have been updated under the assumption of a standardised overall 2% yearly cost increase.

1. **Analysing bioenergy sources**

For this paper wood chips and straw bales are assumed to be roadside ready for loading onto a trailer for the supply to a densification plant. We assume straw bales with water contents of 15%wb (moisture on wet basis) and wood chips of 30%wb, bulk densities of 193 kg m-3 and 276 kg m-3 and energy contents of 17.2 MJ kg-1 and 18.4 MJ kg-1 gross calorific value respectively (Francescato et al., 2008; Rotter and Rohrhofer, 2014). Yearly feedstock yields and accessibilities vary strongly depending on e.g. field productivity, average field size and agricultural practices for straw bundling. Pudelko et al., (2015) state a range based on a feedstock potential assessment of 0.7 t ha-1 to 5.5 t ha-1 for wheat straw. We use the average of 3.1 t ha-1 for the simulation, which is comparable to about 3.5 t ha-1 based on Gerssen-Gondelach et al., (2014). A yearly wood chip residues yield of about 0.7 t ha-1 is adopted from Gerssen-Gondelach et al., (2014) and a forest residue yield of 0.1 t ha-1 from Svanberg et al., (2013) for the sensitivity analysis. A roadside collected straw bale price of 75€ tWM-1 is discussed in Pudelko et al., (2015) when 20% of the potentially harvestable straw is left on the field (based on wet biomass). Due to fertiliser costs that have to be refunded when 100% of the produced straw is harvested, this price can go up to 100€ tWM-1 and as low as 48€ tWM-1 if 50% of straw is left on the field. In line with the same publication we assume a roadside price of 50€ tWM-1 for wood chips for the year 2015.

Table 16: Biomass feedstock specifications based on (Rotter and Rohrhofer, 2014), (Francescato et al., 2008) (Pudelko et al., 2015), (Svanberg et al., 2013), (Gerssen-Gondelach et al., 2014)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Feedstock** | **Characteristic** | **Value** | **Unit** | **Sources** |
| Wheat straw | Bulk density (fresh) | 193 | kg/m^3 | (Rotter and Rohrhofer, 2014), Table 6 |
| Wood chips | Bulk density | 276 | kg/m^3 | (Francescato et al., 2008), Table 1.6 |
| Wheat straw | Roadside price (if 80% collected) | 79,6 | €\_2017/t | (Pudelko et al., 2015), Fig11 |
| Wood chips | Roadside price | 53.1 | €\_2017/t | (Pudelko et al., 2015), Fig11 |
| Wheat straw | Gross calorific value | 17.2 | MJ/kg | (Francescato et al., 2008), Table 2.7.1 |
| Wood chips | Gross calorific value | 18.4 | MJ/kg | (Francescato et al., 2008), Table 2.7.1 |
| Wheat straw | Moisture content | 15 | % | (Francescato et al., 2008), Table 1.6 |
| Wood chips | Mositure content | 30 | % | (Francescato et al., 2008), Table 1.6 |
| Wheat straw | Yield & accessability | 3.095 | t/ha\*a | (Pudelko et al., 2015), p.24 |
| Wood chips | Yield & accessability | 0.0975 | t/ha\*a | (Svanberg et al., 2013), Table1 |
| Wheat straw | Yield & accessability | 3.488 | t/ha\*a | (Gerssen-Gondelach et al., 2014), Table3 |
| Wood chips | Yield & accessability | 0.652 | t/ha\*a | (Gerssen-Gondelach et al., 2014), Table3 |

Supply of feedstock takes place with either a tractor or a truck and an attached trailer. Parameters for the techno-economic evaluation of the feedstock supply step includes handling costs, variable costs per distance including labour and fuel, the maximal cargo capacity in tonnes and the design ratio of the transportation mode in [kg m-³] indicating the minimum density of the transported good. Lower densities lead to derating through not fully using the maximal cargo capacity. All values for feedstock supply are based on or directly taken from Rotter and Rohrhofer, (2014) who documented costs of straw and chips supply including derating effects. In their tables they compare different handling assets including front-end loaders, telescopic handler, forklift trucks and in case of wood chips, container tipping options and handling of roll-off containers. We adopt averages of 1.6 €2014 tDM-1 (based on dry biomass) and 3.9 €2014 tDM-1 for straw and chips respectively. Costs of different handling assets deviate from this average by 42% and 35% for the two feedstock types respectively. Waiting time costs of 33.1€2014 h-1 and 38.5€2014 h-1 are adopted for waiting trucks and tractors respectively while loading of one dry tonne straw are stated to last 1.3 minutes for straw and 1.9 minutes for chips. Distance variable costs range from about 0.2 €2014 tDM-1km-1 to 0.4 €2014 tDM-1km-1 depending on transport mode and transported feedstock.

Table 17: Feedstock supply mode specifications based on (Rotter and Rohrhofer, 2014)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Transport-mode** | **Characteristic** | **Value** | **Unit** | **Source** |
| Tractor\_chips | Design ratio | 306 | kg/m^3 | (Rotter and Rohrhofer, 2014), Table11 |
| Tractor\_straw | Design ratio | 202 | kg/m^3 | (Rotter and Rohrhofer, 2014), Table11 |
| Truck\_chips | Design ratio | 217 | kg/m^3 | (Rotter and Rohrhofer, 2014), Table11 |
| Truck\_straw | Design ratio | 217 | kg/m^3 | (Rotter and Rohrhofer, 2014), Table11 |
| Tractor\_straw | (Un-) loading cost | 1.73 | €\_2017/tDM | (Rotter and Rohrhofer, 2014), Table28 |
| Tractor\_chips | (Un-) loading cost | 4.15 | €\_2017/tDM | (Rotter and Rohrhofer, 2014), Table28 |
| Truck\_straw | (Un-) loading cost | 1.73 | €\_2017/tDM | (Rotter and Rohrhofer, 2014), Table28 |
| Truck\_chips | (Un-) loading cost | 4.15 | €\_2017/tDM | (Rotter and Rohrhofer, 2014), Table28 |
| Tractor\_straw | Variable cost\_incl labour.&.fuel | 0.36 | €\_2017/tDMkm | (Rotter and Rohrhofer, 2014), Table24 |
| Tractor\_chips | Variable cost\_incl labour.&.fuel | 0.39 | €\_2017/tDMkm | (Rotter and Rohrhofer, 2014), Table24 |
| Truck\_straw | Variable cost\_incl labour.&.fuel | 0.16 | €\_2017/tDMkm | (Rotter and Rohrhofer, 2014), Table24 |
| Truck\_chips | Variable cost\_incl labour.&.fuel | 0.21 | €\_2017/tDMkm | (Rotter and Rohrhofer, 2014), Table24 |
| Truck\_straw |  | 0.70 | €\_2017/tDM | (Rotter and Rohrhofer, 2014), Table 27 |
| Truck\_chips |  | 1.11 | €\_2017/tDM | (Rotter and Rohrhofer, 2014), Table 27 |
| Tractor\_straw |  | 0.82 | €\_2017/tDM | (Rotter and Rohrhofer, 2014), Table 27 |
| Tractor\_chips |  | 1.29 | €\_2017/tDM | (Rotter and Rohrhofer, 2014), Table 27 |

1. **Biomass densification technologies**

Adjusted for inflation (of yearly 2%) investment costs of about 4.3\*106 €2017 are assumed for a conventional pellet plant with an output of 40 kt a-1 (Obernberger and Thek, 2010). In comparison, a SECTOR meeting concluded in 20 to 25\*106 €2014 for a 100 kt a-1 torrefaction plant based on wood chips and a factor of 1.3 increased investment costs for using straw instead of chips as a lower density feedstock (Arpiainen et al., 2014). Investment costs for about 150 kt a-1 syncrude oil output is estimated with 67\*106 €2014 (Mireles et al., 2015). Investment costs are annualised using an interest rate of 10% and a depreciation time of 20 years for torrefaction and pelletisation as well as for the pyrolysis pathways. Lower interest rates of 6% are assumed in the discussed reference for traditional pelletisation and are also implemented in the simulation to reflect lower risks for the commercial technology.

Variable costs excluding feedstock costs and energy costs for the evaporation of surplus water content result in 1.8 €2017 GJ-1 and 1.6 €2017 GJ-1 specified on the energy content of the produced straw- and wood pellets respectively (Obernberger and Thek, 2010). Net calorific values of 15.2 MJ kg-1 for straw pellets, based on a reduction of the moisture content to 10%, and an average value of 16.0 MJ kg-1 for wood pellets based on Thrän et al., (2016) are assumed. According to Arpiainen et al., (2014) variable costs excluding feedstock and energy costs are adapted with 2.5 €2017 GJ-1 and 1.9 €2017 GJ-1 based on the energy content of produced torrefied straw- and wood pellets respectively. (Batidzirai et al., 2013) discuss a range of net calorific values for torrefied straw pellets of 17 to 18 GJ t-1 while Thrän et al., (2016) summarise a range of 17 to 24 GJ t-1 for torrefied pellets based on wood chips. The averages are used for the simulation in this thesis. In Rotter and Rohrhofer, (2014) a detailed table for techno-economic assessment of a fast pyrolysis plant is outlined. Excluding energy- and feedstock about 4.8 €2017 GJ-1 can be extracted as variable costs for operating a fast pyrolysis plant. We adopt this value for pyrolysis oil production based on straw and wood chips. Beside the detailed techno-economic summary in the discussed project deliverables, no comparative assessments of costs and product specifications based on the different feedstocks are outlined in the project. We adopt the results from fast pyrolysis experiments from Trinh et al., (2013) who state net calorific values of pyrolysis oil (without char) based on straw and wood of 17.6 GJ t-1 and 17.4  GJ t-1 respectively.

Table 18: Densified bioenergy carriers specifications based on (Francescato et al., 2008)(Rotter and Rohrhofer, 2014),(Thrän et al., 2016),(Batidzirai et al., 2013),(Trinh et al., 2013)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Energy carrier** | **Characteristic** | **Value** | **Unit** | **Source** |
| Straw pellets | Bulk density | 575 | kg/m^3 | (Batidzirai et al., 2013), p.127 |
| Straw pellets | Energy content | 15.2 | MJ/kg | (Francescato et al., 2008), Table 2.7.1 |
| Wood pellets | Bulk density | 600 | kg/m^3 | (Thrän et al., 2016), Table 3 |
| Wood pellets | Energy content | 16 | MJ/kg | (Thrän et al., 2016), Table 3 |
| Torr. Straw pellets | Bulk density | 695 | kg/m^3 | (Batidzirai et al., 2013), p.127 |
| Torr. Straw pellets | Energy density | 17.5 | GJ/m^3 | (Batidzirai et al., 2013), p.127 |
| Torr. Wood pellets | Bulk density | 675 | kg/m^3 | (Thrän et al., 2016), Table 3 |
| Torr. Wood pellets | Energy content | 20.50 | MJ/kg | (Thrän et al., 2016), Table 3 |
| Wheat straw | Bulk density | 193 | kg/m^3 | (Rotter and Rohrhofer, 2014), p.15 |
| Wood chips | Bulk density | 275.5 | kg/m^3 | (Francescato et al., 2008),Table 1.6 |
| Wheat straw | Energy content | 14.2540 | MJ/kg | (Francescato et al., 2008), Table 2.7.1 |
| Wood chips | Energy content | 12.1480 | MJ/kg | (Francescato et al., 2008), Table 2.7.1 |
| Biosyncrude\_wheat | Bulk density | 1150 | kg/m^3 | (Trinh et al., 2013), Table 5 |
| Biosyncrude\_wheat | Energy content | 17.6 | MJ/kg | (Trinh et al., 2013), Table 5 |
| Biosyncrude\_wood | Bulk density | 1120 | kg/m^3 | (Trinh et al., 2013), Table 5 |
| Biosyncrude\_wood | Energy content | 17.4 | MJ/kg | (Trinh et al., 2013), Table 5 |

Mass yields on dry biomass basis for torrefaction are discussed in Koppejan et al. (2015). For three different technologies yields of about 79%, 76% and 81% are stated. We adopt the average of 79% for this thesis. Trinh et al., (2013) find mass yields of 60% and 68% for pyrolysis oil based on straw and wood respectively. For traditional pelletisation we assume no dry mass loss since no fractioning of the single components of the feedstock takes place.

Energy costs are calculated based on the differences between feedstock moisture content and a 10%wb dried input into the various processes. To assure comparability between the technologies and produced energy carriers we assume that all drying processes are performed with a natural gas furnace and an OECD average industry natural gas price of 25 €2017 MWh-1 (OECD, IEA, 2018). The torrefaction and fast pyrolysis process result in energy yields of about 89% for torrefaction and 56% for straw pyrolysis and 74% for wood chips pyrolysis respectively (Henrich et al., 2015; Koppejan et al., 2015). The energy content of the torrefaction gas is discussed to be sufficient to run the process auto thermally (SECTOR, 2014). The combustion energy of the pyrolysis gases also suffice for a self-sustained fast pyrolysis process (Henrich et al., 2015, p. 5).

Table 19: Densification technology characteristics based on SECTOR Meeting, Berlin 2014 and (Obernberger and Thek, 2010)(Arpiainen et al., 2014)(Mireles et al., 2015),(Trinh et al., 2013)(Koppejan et al., 2015)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Technology** | **Characteristic** | **Value** | **Unit** | **Sources** |
| StO | Investment costs | 71 | M€\_2017 | (Mireles et al., 2015), Annex J |
| StO | Reference Size | 148056 | t\_out/year | (Mireles et al., 2015), Annex J |
| StO | Variable&general expenses | 4.8 | €\_2017/GJ\_out | (Mireles et al., 2015), Annex J |
| StO | Energy yield | 56% | GJ\_out/GJ\_in | (Trinh et al., 2013) |
| StP | Investment costs | 4.3 | M€\_2017 | (Obernberger and Thek, 2010) |
| StP | Reference Size | 40000 | t\_out/year | (Obernberger and Thek, 2010) |
| StP | Variable&general expenses | 1.84 | €\_2017/GJ\_out | (Obernberger and Thek, 2010) |
| StP | Energy yield | 100% | GJ\_out/GJ\_in | (Obernberger and Thek, 2010) |
| WtP | Investment costs | 4.3 | M€\_2017 | (Obernberger and Thek, 2010) |
| WtP | Reference Size | 40000 | t\_out/year | (Obernberger and Thek, 2010) |
| WtP | Variable&general expenses | 1.63 | €\_2017/GJ\_out | (Obernberger and Thek, 2010) |
| WtP | Energy yield | 100% | GJ\_out/GJ\_in | (Obernberger and Thek, 2010) |
| StT | Investment costs | 31.04 | M€\_2017 | SECTOR Meeting,  Berlin 29.01.2014 |
| StT | Reference Size | 100000 | t\_out/year | SECTOR Meeting,  Berlin 29.01.2014 |
| StT | Variable&general expenses | 2.54 | €\_2017/GJ\_out | (Arpiainen et al., 2014), Table 10 |
| StT | Energy yield | 89% | GJ\_out/GJ\_in | (Koppejan et al., 2015), Table3.2 |
| WtT | Investment costs | 23.9 | M€\_2017 | SECTOR Meeting,  Berlin 29.01.2014 |
| WtT | Reference Size | 100000 | t\_out/year | SECTOR Meeting,  Berlin 29.01.2014 |
| WtT | Variable&general expenses | 1.94 | €\_2017/GJ\_out | (Arpiainen et al., 2014), Table 10 |
| WtT | Energy yield | 89% | GJ\_out/GJ\_in | (Koppejan et al., 2015), Table3.2 |
| StO | Mass yield | 60.0% | on dry mass basis | (Trinh et al., 2013) |
| StT | Mass yield | 78.7% | on dry mass basis | (Koppejan et al., 2015), Table3.2 |
| WtT | Mass yield | 78.7% | on dry mass basis | (Koppejan et al., 2015), Table3.2 |
| StP | Mass yield | 100% | on dry mass basis | (Obernberger and Thek, 2010) |
| WtP | Mass yield | 100% | on dry mass basis | (Obernberger and Thek, 2010) |
| WtO | Investment costs | 71 | M€\_2017 | (Mireles et al., 2015), Annex J |
| WtO | Reference Size | 148056 | t\_out/year | (Mireles et al., 2015), Annex J |
| WtO | Variable&general expenses | 4.8 | €\_2017/GJ\_out | (Mireles et al., 2015), Annex J |
| WtO | Energy yield | 74% | GJ\_out/GJ\_in | (Trinh et al., 2013) |
| WtO | Mass yield | 68.0% | on dry mass basis | (Trinh et al., 2013) |

1. **Distribution of bioenergy carriers**

Distance costs for transportation are estimated based on Hoefnagels et al., (2013) and fuel consumption values are adopted from the same reference. We assume labor costs of 25.0 €\*h-1 and a diesel price of about 23.0 €\*GJ-1 based on an energy density of 36.9 MJ\*litre-1 (ACEA, 2013) and a 1.1$/€ conversion rate (Statista, 2018). Diesel prices are average global prices payed in IEA, (2018). Prices for IFO380, used for ocean shipping can be roughly estimated using Brent crude oil prices as indicator: For 2017 we assume an average Brent Oil price of 11.4 €\*GJ-1 based on a barrel oil equivalent of 6.1 GJ\*barrel-1 and (IEA, 2018). According to ShipandBunker, (2015) IFO380 was priced with an discount at 70-80% to the crude price (in the time frame Nov.2012-Dec.2014). We further use the averaged 75% discount.

Furthermore for empty trips, which could be necessary to return the vehicle to the densification plant, only values for road and ship transport are calculated. An about 38% decreased fuel consumption has a significant impact on the variable costs (-12%) for road transport and a 17% IFO consumption to -7% for shipping, while for rail transport no difference between empty and full load trips is assumed based on the stated fuel and labor prices as well as input parameter from Hoefnagels et al., (2013). Specifying costs on the transported payload results in about 8.0€2017cent\*tkm-1 for road, 0.6€2017cent\*tkm-1 for rail and 0.02€2017cent\*tkm-1 ocean transport respectively including empty backhaul.

No literature is known to the authors comparing loading and unloading options of pellets, torrefied pellets and pyrolysis oil. However, Hoefnagels et al., (2011) state cost ranges of 1.1-2.7 €\*t-1 for transshipment to truck and ships and 1.9 to 4.5 €\*t-1 to rails. We adopt the averages of 4.1 €2017/t and 6.7 €2017/t respectively for all bioenergy carriers for loading plus unloading.

Furthermore no costs for dedicated wood pellet silos or pyrolysis oil storage tanks could be acquired. Rotter and Rohrhofer, (2014) state investment costs of 7.8\*105 €2012 for a covered intermediary storage of 7\*103 m³. Tank Storage Magazine, (2012) states 26\*106 €2012 costs for an 11\*103 m³ storage for petroleum products. Operation and maintenance costs shares of 7.6% of the investment costs per year are adopted from Rotter and Rohrhofer, (2014). This results in yearly storage costs of about 16.5 €2017\*m-3 for solid bioenergy carriers and 36.6 €2017\*m-3 for pyrolysis oil. Assuming wood pellets to be stored we derive daily costs of 7 €cent\*t-1 which is comparable to the estimated 8 €cent\*t-1 stated in Hoefnagels et al., (2011). No comparative assessment for liquid bioenergy carries could be found in literature.

Table 20: Bioenergy carrier distribution characteristics based on (Rotter and Rohrhofer, 2014)(Hoefnagels et al., 2013),(Tank Storage Magazine, 2012)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Transport-mode** | **Characteristic** | **Value** | **Unit** | **Source** |
| Ocean | Design ratio | 600 | kg/m^3 | (Hoefnagels et al., 2013), Table 5 |
| Rail | Design ratio | 400 | kg/m^3 | (Hoefnagels et al., 2013), Table 5 |
| Rail\_oil | Design ratio | 684 | kg/m^3 | (Rotter and Rohrhofer, 2014), Table 36 |
| Truck | Design ratio | 225 | kg/m^3 | (Hoefnagels et al., 2013) |
| Truck\_oil | Design ratio | 563 | kg/m^3 | (Rotter and Rohrhofer, 2014), Table37 |
| Ocean\_oil | Design ratio | 600 | kg/m^3 | (Hoefnagels et al., 2013) |
| Truck | (Un-) loading cost | 4.12 | €\_2017/t | (Hoefnagels et al., 2013), Table 3-5 |
| Rail | (Un-) loading cost | 6.69 | €\_2017/t | (Hoefnagels et al., 2013), Table 3-5 |
| Ocean | (Un-) loading cost | 4.12 | €\_2017/t | (Hoefnagels et al., 2013), Table 3-5 |
| Truck\_oil | (Un-) loading cost | 4.12 | €\_2017/t | (Hoefnagels et al., 2013), Table 3-5 |
| Rail\_oil | (Un-) loading cost | 6.69 | €\_2017/t | (Hoefnagels et al., 2013), Table 3-5 |
| Ocean\_oil | (Un-) loading cost | 4.12 | €\_2017/t | (Hoefnagels et al., 2013), Table 3-5 |
| Truck\_oil | Variable cost\_incl labour.&.fuel | 0.0803 | €\_2017/t\*km | (Hoefnagels et al., 2013) |
| Truck | Variable cost\_incl labour.&.fuel | 0.0803 | €\_2017/t\*km | (Hoefnagels et al., 2013) |
| Rail | Variable cost\_incl labour.&.fuel | 0.0056 | €\_2017/t\*km | (Hoefnagels et al., 2013) |
| Ocean | Variable cost\_incl labour.&.fuel | 0.0022 | €\_2017/t\*km | (Hoefnagels et al., 2013) |
| Rail\_oil | Variable cost\_incl labour.&.fuel | 0.0056 | €\_2017/t\*km | (Hoefnagels et al., 2013) |
| Ocean\_oil | Variable cost\_incl labour.&.fuel | 0.0022 | €\_2017/t\*km | (Hoefnagels et al., 2013) |
| Storage | Covered storage | 16.51 | €\_2017/m^3\*a | (Rotter and Rohrhofer, 2014), Table30 |
| Storage\_oil | Tank farm | 36.59 | €\_2017/m^3\*a | (Tank Storage Magazine, 2012) |

1. **Bioenergy conversion costs**

For small scale combustion European averages for heating systems are calculated using weighted averages from three exemplary countries considered as a representative cross-section (Spain, Germany and Rumania) based on data from the ENTRANZE database (ENTRANZE, 2014). With estimated 1,800 heating hours per year operation and maintenance (O&M) as well as annuities are calculated for wood pellets and oil based heating systems. Average utility costs of 22.4 €\*GJ-1 derived heat (with about 8% O&M) and 15.3 €\*GJ-1 (with about 9% O&M) are estimated for pellet and oil boilers respectively. Conversion efficiency are derived from the same database for single and central pellets boilers (84%) and for single, central and condensing central oil boilers (80%). An average tax of 13% was payed for wood pellets in the main EU residential wood pellets consuming countries in 2017. We adopt this value for all densified bioenergy carriers in the residential heating case.

Arpiainen et al., (2015) estimate economics of co-firing coal with traditional and torrefied wood pellets. By using harmonised cost-figures of a 400 MWel (MW electricity production) power plant co-fired with 10% wood pellets, extra yearly utility costs are estimated at 2.65\*106 €2013 and 0.79\*106 €2013 for the two densification technologies excluding the fuel costs respectively. These numbers are based on 2.16 PJ yearly biomass input and 40% efficiency for coal, torrefied pellets and 39.7% efficiency for white pellets. Lüschen and Madlener, (2013) estimates cost composition for electricity production from coal fired power plants. With 100% coal firing costs are estimated at 71 €2009\*MWhel with 49% share in utility costs based on a 600 MWel sized power plant with an efficiency of 40% and 6,000 full-load hours. Co-firing of 10% pyrolysis oil is possible in coal-fired power plants with minor adjustments (Czernik and Bridgwater, 2004), we assume no extra costs. We derive utility costs of about 15.5 €2017\*GJel-1, 12.6 €2017\*GJel-1 and 11.3 €2017\*GJel-1 for wood pellets, torrefied wood pellets and pyrolysis oil co-firing respectively.

For gasification and FT-synthesis efficiencies of 49%,43% and 47% based on a comparative study from (Meerman et al., 2012) for oil, pellets and torrefied pellets are adopted respectively. Utility costs of 11.0 €2017\*GJFT-1, 14.6 €2017\*GJFT-1 and 12.2 €2017\*GJFT-1 are derived for a 2.0 GWth (thermal) coal equivalent input gasification and FT-synthesis plant. Furthermore electricity is co-produced with 10%, 12% and 11% efficiencies for the three solid energy carriers which is assumed to be sold to the European electricity market price. For pyrolysis oil to Fischer Tropsch diesel we adopt the coal fired key figures, assuming that no derating of the capacity takes place.

1. **Energy reference prices**

Reference prices for residential heating are calculated based on data from the ENTRANZE database (ENTRANZE, 2014) and the discussed representative European cross-section. Average utility costs are estimated with 12.8 €\*GJ-1 and a share of 6% coal, 9% electricity, 20% oil and 54% gas boilers as well as 11% district heating connected residents. An average OECD-EU household bitumeus coal price of 7.6 €2016\*GJ-1 (OECD, IEA, 2018), EU28 average household prices for 25.4 €2017\*GJ-1 payed for electricity, 10.9 €2017\*GJ-1 payed for natural gas (Eurostat, 2018) and 12.7 €2017\*GJ-1 for domestic fuel oil (EC, 2018) are further used. This results in average heating costs of 25.2 €2017\*GJ-1. With minimum and maximum fuel values a range between 19.6 and 36.9 €2014\*GJ-1 can be estimated.

For co-firing an average 2017 electricity prices without taxes and levies for the largest consumer group from Eurostat, (2018) of 11.5 €cent\*kWh-1 are used as a reference. The gasification and FT-diesel production path is compared to average EU28 diesel prices without taxes and levies from EC, (2018) with 14.1 €2017\*GJ-1 assuming a net calorific value of 10.1 kWh\*liter-1 (Biermayr, 2016). Average diesel prices ranged between 12.7 and 14.9 €\*GJ-1 in 2014.

Table 21: Bioenergy conversion characteristics based on (OECD, IEA, 2018)(ENTRANZE, 2014)(Arpiainen et al., 2015)(Lüschen and Madlener, 2013)(Meerman et al., 2012)(EC, 2018),(Held et al., 2014)(Eurostat, 2018)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Technology** | **Characteristic** | **Value** | **Unit** | **Sources** |
| Res\_pell | without fuel | 23.8 | €\_2017/GJ\_out | (ENTRANZE, 2014) |
| Res\_torrpell | without fuel | 23.8 | €\_2017/GJ\_out | (ENTRANZE, 2014) |
| Res\_syn | without fuel | 16.2 | €\_2017/GJ\_out | (ENTRANZE, 2014) |
| Co\_pell | without fuel | 15.5 | €\_2017/GJ\_out | (Lüschen and Madlener, 2013), Fig.5 |
| Co\_torrpell | without fuel | 12.6 | €\_2017/GJ\_out | (Lüschen and Madlener, 2013), Fig.5 |
| FT\_pell | without fuel | 14.6 | €\_2017/GJ\_out | (Meerman et al., 2012), Fig.13 |
| FT\_torrpell | without fuel | 12.2 | €\_2017/GJ\_out | (Meerman et al., 2012), Fig.13 |
| FT\_syn | without fuel | 11.0 | €\_2017/GJ\_out | (Meerman et al., 2012), Fig.13 |
| Co\_syn | without fuel | 11.3 | €\_2017/GJ\_out | (Lüschen and Madlener, 2013), Fig.5 |
| Ind\_pell |  | 35.4 | €\_2017/GJ\_out | (Held et al., 2014) |
| Ind\_torrpell |  | 35.4 | €\_2017/GJ\_out | (Held et al., 2014) |
| Ind\_syn |  | 35.4 | €\_2017/GJ\_out | (Held et al., 2014) |
| Co\_torrpell | Yield cofired power plant | 40% |  | (Arpiainen et al., 2015) |
| Co\_pell | Yield cofired power plant | 40% |  | (Arpiainen et al., 2015) |
| FT\_pell | FT Efficiency HHV | 55% |  | (Meerman et al., 2012), Table.1 |
| FT\_torrpell | FT Efficiency HHV | 58% |  | (Meerman et al., 2012), Table.1 |
| FT\_syn | Energy Yield | 59% |  | (Meerman et al., 2012), Table.1 |
| Co\_syn | Energy Yield | 40% |  | (Arpiainen et al., 2015) |
| Ind\_pell |  | 89% |  | (Held et al., 2014) |
| Ind\_torrpell |  | 89% |  | (Held et al., 2014) |
| Ind\_syn |  | 89% |  | (Held et al., 2014) |
| Res\_pell | Efficiency | 84% |  | (ENTRANZE, 2014) |
| Res\_torrpell | Efficiency | 84% |  | (ENTRANZE, 2014) |
| Res\_syn | Efficiency | 80% |  | (ENTRANZE, 2014) |
| FT\_pell | FT Efficiency HHV | 12% |  | (Meerman et al., 2012), Table.1 |
| FT\_torrpell | FT Efficiency HHV | 11% |  | (Meerman et al., 2012), Table.1 |
| FT\_syn | Energy Yield | 10% |  | (Meerman et al., 2012), Table.1 |
| Ind\_pell |  | 25% |  | (Held et al., 2014) |
| Ind\_torrpell |  | 25% |  | (Held et al., 2014) |
| Ind\_syn |  | 25% |  | (Held et al., 2014) |
| Diesel | EU28 2014 average w/o taxes and levies | 14.1 | €\_2017/GJ | (EC, 2018) |
| Electricity | EU28 average electricity price for largest consumers w/o taxes and levies | 11.5 | €\_2017/GJ | (Eurostat, 2018) |
| Residential | EU28 average heating costs for residential | 25.2 | €\_2017/GJ | (Held et al., 2014) (EC, 2018) (Eurostat, 2018) (OECD, IEA, 2018) |

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