Danish Energy Agency

The AD Model for alternative Fuels

Model documentation

Contents

1 History, purpose and scope (2 pages) 2

2 Model structure (3 pages) 3

3 Energy sources (2 pages) 6

3.1 Feedstocks 6

3.2 Process energy 8

3.3 By-products 8

4 Feedstock conversion technologies 11

4.1 Data 11

4.2 Methodology (2 pages) 12

5 Transmission of intermediaries 14

6 Intermediate conversion (2 pages) 15

6.1 Data 15

6.2 Methodology 15

7 Distribution of fuel (1 pages) 17

8 Motor technologies 18

8.1 General (~1 pages) 18

8.2 Hybrid motors (~1 pages) 18

8.3 Fuel mixes (~1 page) 18

9 Modelled pathways 19

10 Technological development 21

11 Model interface 22

11.1 Presentation of results 22

11.2 Adding new technologies and pathways 23

# History, purpose and scope (2 pages)

Since 2007, COWI has been developing the AD model the Danish Energy Agency in various ongoing projects. The purpose of the model is to provide a consistent analysis of costs and emissions from various transport technology pathways.

The methodology used in the project is inspired by e.g. CONCAWE (2006) and VIEWLS (2005a,b) where various fuel and transport technologies are described in so-called pathways.

A pathway consists of the whole production chain from production of feedstocks such as crude oil, crops or biomass through various conversion processes, transport and distribution until the final use in the motor of a particular vehicle.

By using the pathway approach, it is possible to account for all the various steps in the production and use of transport fuels in a systematic way. In particular, it is possible to streamline and standardise the assumptions on feedstock and process energy inputs, and their conversion and distribution losses. The standardisation implies that it also is possible to compare the costs and emissions of various pathways.

The scope of the model is therefore a life cycle assessment of the socio-economics selected environmental effects, notably greenhouse gasses including ILUC, but also hazardous emissions such as SO₂, NOX and particulate matter (PM).

The effect analysed is the marginal effect of shifting a tiny amount of transport activity from one pathway to another, e.g. 1 km of driving with a gasoline car to 1 km with a 2nd generation ethanol car.

As Denmark is a small open economy, one could argue that actions taken in Denmark in relation to choice of transport technologies should not affect world market prices for feedstocks and thereby neither local Danish prices for energy. This is, however, not likely to be true for two reasons:

* The transport technology choice is motivated by a global agenda for reducing greenhouse gas emissions. Therefore, Denmark is expected to some extent to move in tandem with other countries in its technology choices
* An important part of the transport technology choice relates increased use of electricity in the transport sector, which in turn might allow increased use of intermittent sources of electricity such as wind power. Therefore, larger changes in transport technology choice might facilitate other changes in the energy sector which again affect the marginal costs and emissions of the energy used in transport

For these two reasons, the AD model is not necessarily well suited to analyse larger shifts between the uses of different pathways, as the model does not account for cost and marginal emission changes in the local energy system or global market for feedstocks.

# Model structure

The AD model has a "bottom-up" structure where costs and emissions are added to the each of the different pathways modelled in successive layers of increasing refinement from feedstock to fuel. These layers are

1. Upstream processes for production and transport of feedstocks to the (bio)refinery
2. Converting feedstock into intermediate product (e.g. syngas from thermal gasification
3. Transport/transmission and losses of intermediate product (e.g. natural gas net)
4. Converting intermediate product into transport fuel (e.g. syngas to fuel)
5. Distribution of fuels (e.g. tanker trucks, recharging/compression stations)
6. Conversion in motors from energy to traffic work

Often, the feedstock conversion process result in a ready-to-use fuel. In these cases, layer 3 and 4 are not used. Others (such and thermal gasification + synthetisation) these additional two layers are needed.

In each layer various process energy uses, production of by-products and conversion losses occur. All pathways are analysed using the layering and loss structure depicted in Figure 1.

Figure 1 Layered structure of the AD model



In Figure 1, the blue coloured boxed indicates the conversion technology specific parts of the data used for computing the costs and emissions in each pathway. The conversion technology data needed in the AD model are briefly described in Table 1. The conversion technologies and their data are described in more detail in section 5, 6, and 8.

Table 1 Overview of input data for the conversion technologies

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Feedstock conversion** | **Intermediate conversion** | **Motor conversion** |
| **Conversion efficiency** | GJ intermediate / GJ feedstock | GJ fuel / GJ intermediate | km / GJ fuel |
| **Process energy** | GJ energy/ GJ feedstock | GJ energy / GJ intermediate | N/A |
| **Costs** | CAPEX + OPEX + inputs | CAPEX + OPEX + inputs | CAPEX + OPEX + inputs |
| **Emissions** | Feedstock + input energy use | Intermediate + input energy use | Fuels |

In Figure 1 the light grey arrows indicates data used for computing the input costs and emissions from inputs in each pathway. The scope of the costs and emissions are briefly described in Table 2, and treated in more detail in section 4 and 7.

Table 2 Overview of input data for inputs into conversion and transport, transmission and distribution

|  |  |
| --- | --- |
| **Input data** | **Coverage** |
| **Feedstock process** | **Covers:** Extraction, cultivation, harvest, transport  **Costs:** Land & resource rents, OPEX and CAPEX  **Emissions:** Transport and energy use, soil process, losses |
| **Feedstock ILUC** | **Emissions:** Land use change with 100 year GWP |
| **Process energy and by-products** | **Covers:** Electricity, heat, diesel, chemicals, by-products  **Costs:** OPEX & CAPEX, marginal input costs and value  **Emissions:** Transport and energy use valued at marginal emissions |
| **Transport / transmission** | **Covers:** Power and natural gas transmission net  **Costs:** CAPEX, OPEX and energy  **Emissions:** Electricity losses, compression energy |
| **Distribution** | **Covers:** Tanker transport, compression of gas, loss in charger stations  **Costs:** CAPEX and OPEX and energy  **Emissions:** Transport, electricity use |

Some of the conversion processes also produce by-products, e.g. production of RME using rapeseed has rape seed cake and glycerol as by-product. Most of these by-products are handled such that the avoided emissions from the by-products' substitution of virgin materials are subtracted from the emission footprint of the main product.

One notable exception is refinery products, e.g. the co-production of gasoline and diesel. For these products, the total process energy and upstream emissions from the feedstock is distributed between the by-products according to their market value when leaving the refinery. This choice is described in more detail in section 3.3.

# Energy sources

As shown in Figure 1 the energy use and the associated emission in the AD model are split into five distinct types:

1. Production of **feedstocks**
2. **Process energy** use in the feedstock conversion technologies
3. Energy use for **transmission** of intermediates
4. **Process energy** use in the intermediate conversion technologies
5. Energy use for **distribution** of the fuel

The process energy use for both conversion of feedstock and intermediaries has been streamlined into using the same data on marginal costs and emissions of each category of process energy use, so these two types are described together.

## Feedstocks

The AD model presently operates with XX feedstocks divided into four general types:

* **Crop feedstocks:** Wheat, rape and sugar beets,
* **Ligneous feedstocks:** Straw and wood chips
* **Fossil feedstocks:** Crude oil and natural gas
* **Electricity as feedstock:** Continuous and balancing electricity

The scope and data for these different types of feedstocks are described in this section.

### Crop feedstocks

The crop feedstocks are wheat, rape and sugar beets. Emission data for CO₂ and process energy use stemming from cultivation, harvest and transport are found in CONCAWE (2011). Multiplying the process energy use with emission factors for truck transport, the AD model also derives SO₂ and NOX emissions from the use of agricultural machinery and trucks from transport.

The prices for the crop feedstocks are found on two Danish agricultural websites: www.dlg.dk (wheat and rape) and [www.sukkerroer.nu](http://www.sukkerroer.nu) (sugar beets).

The IFPRI (2010) study presents the ILUC emissions only in the form of emissions per GJ fuel. Since the AD model departs from emissions per GJ feedstock, the numbers must be transformed to feedstock basis using the AD model assumptions on efficiencies and bi-products. With the notation

* Ufeed is the unknown unit emission from feedstocks
* Uby is the unknown unit emission from substituted byproducts
* Ufuel is the known unit emission from fuel
* Efuel is the known conversion efficiency from feedstock to fuel
* Eby is the known conversion efficiency from feedstock to by-product

we can state the emission balance in the conversion process. For lack of data we further assume that the feedstock and the byproduct are each other’s substitutes on

Ufeed – Eby Uby = Efuel Ufuel ⬄ Uby = Ufeed = Ufuel Efuel / ( 1 – Eby )

Until more precise estimates of ILUC effects from crops are available, the values below will be used.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  | **Ufuel** | **Eby** | **Efuel** | **Ufeed & Uby** |
|  |  | **g/MJ fuel** | **% of energy** | **% of energy** | **g/MJ** |
| RME rapeseed | Low IFPRI | 50,6 | 27% | 73% | 16 |
|  | High IFPRI | 53,7 | 27% | 73% | 64 |
| Wheat ethanol | Low IFPRI | 16,0 | 26,8 | 55,6 | 12,1 |
|  | High IFPRI | 37,3 | 26,8 | 55,6 | 28,3 |
| Sugar beet ethanol | Low IFPRI | 16,1 | 39,0 | 57,5 | 16,8 |
|  | High IFPRI | 65,5 | 39,0 | 57,5 | 68,4 |

### Ligneous feedstocks

The ligneous feedstocks are straw and wood chips. Emission data for Indirect Land Use Changes (ILUC) are found in COWI/SDU (2013). Wood chips like biomass is considered to be a world market traded energy good. Due to the likely increasing demand for biomass for energy, the type of biomass harvest will change over time.

The ILUC emissions are heavily dependent on land use policies and in particular management of forests. A best and a worst case developing over time has been identified in the study. These best and worst cases are used for sensitivity analyses in the AD model. The values used are show in

Table 3 ILUC from ligneous feedstocks on an international market (g/MJ)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Boreal** | **Temperate** | **Tropical** | **Average** | **Biomass land use** |
| *Best case* | | | | | |
| 2013+ | 0,0 | 0,0 | 0,0 | 0 | Residues and thinnings |
| 2020+ | -27,0 | -6,0 | -5,0 | -13 | Plantation on low C savannah |
| 2035+ |  |  | 3,0 | 3 | Plantation on high C savannah |
| 2050+ |  |  | 3,0 | 3 | Plantation on high C savannah |
| *Worst case* | | | | | |
| 2013+ | 74,0 | 108,0 | 41,0 | 74 | Harvest from existing forest |
| 2020+ | 104,0 | 194,0 | 67,0 | 122 | Plantation on forest land |
| 2035+ | 104,0 | 194,0 | 67,0 | 122 | Plantation on forest land |
| 2050+ | 104,0 | 194,0 | 67,0 | 122 | Plantation on forest land |

Source: COWI/SDU (2013)

The price data for straw and wood chips are found in Ea Energy Analyses (2013) (medium estimate). In this publication, it is assumed that straw carries 85% of the price of wood chips.

### Fossil feedstocks

The fossil feedstocks are coal, crude oil and natural gas. The data on CO₂ emissions and energy use from extracting these feedstocks have been found in CONCAWE (2011). The prices for these feedstocks are provided by Danish Energy Agency (2012).

### Electricity feedstocks

The AD model also provides electricity feedstocks for use in electric vehicles, production of hydrogen etc. The cost of electricity is based on Danish Energy Agency (2012), with an addition of 100 DKK/MWh for 2020 and onwards due to concerns that the current DEA estimate does not fully account for the long run marginal costs of producing electricity.[[1]](#footnote-1)

The cost of electricity reflects also the cost of distribution to car owners' homes (low voltage distribution) in case of electric vehicles and to decentralised hydrogen producers (low/medium voltage distribution).

The emissions from the electricity feedstock is determined in agreement between COWI and DEA as the long run marginal emissions, which have been deemed to be 96% wind power and 4% gas turbine power. As a sensitivity option, the average Danish emissions (projected to 2035) can also be chosen by the user.

## Process energy

Process energy is used in most conversion technologies. It covers a number of different energy inputs, notably electricity, heat, diesel and various chemicals. In most cases, process energy inputs have exactly the same costs and marginal emissions as the equivalent feedstocks. The feedstocks present in the model are

* Electricity
* Heat
* Natural gas
* Methanol

## By-products

For production processes, which produce by-products (e.g. RME production from rapeseed also produces glycerol and rape seed cake) it is assumed that the by-product substitute virgin materials. This substitution is attributed to the emission footprint of the main product. The model currently handles substitution of virgin materials for the following by-products shown in Table 3:

Table 4 By-product and substitutes

|  |  |
| --- | --- |
| **By-product** | **Substitutes** |
| Green diesel | RME |
| Green gasoline | 1G ethanol |
| Electricity | Electricity production |
| Heat | District heating |
| Biogas | Natural gas |
| Fodder (wheat like) | Wheat (on energy content basis) |
| DDGS | Wheat (on energy content basis) |
| Rapeseed cake | Rapeseed (on energy content basis) |

In some production processes, such as oil refineries, there is no clear alternative production methods. It is therefore not possible to value the virgin materials substituted by the by-products, since the process can only substitute itself. In these cases, we have chosen not to assign a main and one or more by-products.

Instead, we split the emissions from the feedstock and other inputs between the different products in a so-called economic allocation. Economic allocation implies that the emissions caused by producing the feedstock and the process energy is allocated according to the share of the different by-products' share of total market value of all by-products.

This choice is justified by looking at the profit maximisation problem of a monopolist[[2]](#footnote-2) oil refinery producing two goods, 1 and 2 (e.g. diesel and gasoline). Not considering capital costs (which are assumed to be sunk), the refinery has marginal costs for crude oil and energy for processing of the crude oil.

Substituting the demand relations between prices and quantities and differentiating with respect to q1 and q2 gives us the first order conditions for profit optimisation where *ε = dP/dq q/p* represents the market elasticity:

The interpretation is that marginal revenue of each good should always equal marginal costs. We do not know the precise relationship between the marginal costs of each of the goods, so we assume constant marginal costs of c1 and c2 with a fixed relation of c1 = αc2. Substituting this into the two marginal revenue conditions above we get

In order to maximise the revenues, the relationship between the prices of the two goods should always be in the same fixed proportion determined by the market price elasticities of the two goods. Therefore, the price of the two goods should also rise and fall in tandem, for instance in response to changing input (crude oil) prices.

From a socio-economic point of view, it is therefore justifiable to allocate emissions according to the production value (quantity x sales price) of the by-products in cases where there is no obvious other way of measuring the value of the other by-product.

# Feedstock conversion technologies

The AD model describes four groups of feedstock conversion technologies, which convert feedstock into intermediates or in some cases final fuels.

* Fossil fuels from refineries
* Grid based energy (electricity and natural gas)
* Liquid biomass based fuels
* Biogas

The following section describe data and methodology for the feedstock conversion

## Data

The conversion technologies and data sources used for feedstock conversion are shown in Table 4.

Table 5 Overview of feedstock conversion technologies and their data sources

|  |  |
| --- | --- |
| **Feedstock conversion technology** | **Data source** |
| Diesel from crude oil | COWI calculations on emission and energy data from Statoil (2012) and DEA (2013) on economics |
| Gasoline from crude oil |
| Jet fuel from crude oil (JP1) |
| Heavy fuel oil (HFO) |
| Electricity for hydrogen production (industrial consumer loss) | COWI / DEA assumptions |
| Electricity for charging electric vehicles (household losses) | COWI / DEA assumptions |
| Natural gas refining | COWI / DEA assumptions |
| Bio-methanol on wood chips | FORCE (2013), no. 1 |
| 1G ethanol on wheat | FORCE (2013), no. 3 |
| 2G ethanol on straw | FORCE (2013), no. 4 |
| 2G biodiesel on straw | FORCE (2013), no. 7 |
| DME on wood chips | FORCE (2013), no. 9 |
| Bio jet fuel | FORCE (2013), no. 18 |
| RME from rapeseeds | FORCE (2014), no. 19 |
| 1G ethanol on sugar beets | FORCE (2014), no. 20 |
| Biogas | COWI calculations on ENS - Biogas Taskforce (2013) |

For fossil fuels from refineries, the conversion efficiencies from crude oil to various products are interlinked so that the four conversion technologies together give a consistent picture of the production of and emissions from various fuels from a fossil refinery. The economics of the fossil refinery products are based on DEA (2013) estimates on fossil fuel prices, and is not in particular linked to the emission and production data.

The data source for biomass feedstock conversion technologies is FORCE (2013). Here, costs, conversion efficiencies and process energy input requirements are stated for a wide range of technologies. In an addendum, two additional conversion technologies (ethanol from sugar beet and RME with rapeseed as input) has also been provided, see FORCE (2014).

The cost and conversion for biogas is based on DEA – Biogas Taskforce (2013). The model user has an option to vary the composition of inputs into the biogas plant. The base assumption is mainly manure, and a small amount of waste straw from animal production.

Finally, electricity act as feedstock for some intermediate conversion and transport technologies. Here, it is assumed that 4 % of the marginal production of electricity comes from new natural gas fired gas turbines, while the remaining 96 % is wind, and solar energy combined with a minor input of other energy sources. This assumption is based on estimates from DEA (2014).

## Methodology

The accounting of emissions in the conversion of feedstocks departs from the upstream emissions from producing the feedstock, e.g. fuel for machine use, but also emissions connected to direct effects of land use, e.g. emissions from the soil used for feedstock, or leakage emissions from mining or drilling. The data for these emissions are accounted in kg/GJ feedstock.

The process energy use in connection with the conversion process is also accounted for in kg/GJ feedstock. Further, some processes have by-products, which may substitute virgin materials leading to emission reductions elsewhere. These are also accounted for in kg/GJ feedstock.

The sum of feedstock and process energy emission is subtracted the avoided emissions from production of by-products. Finally, the energy conversion efficiency of the conversion technology, *ηF*, is used for scaling the emission from kg/feedstock to kg/intermediate. This is summarised in Table 5.

Table 6 Handling of emission in feedstock conversion

|  |  |  |
| --- | --- | --- |
| **Step** | **Emissions** | **Formula** |
| eA | Feedstock production emissions (per GJ feedstock) | eA1 + eA2 |
| eA1 | - process emissions from production and transport | Data, see sec. 3. |
| eA2 | - indirect land use emissions | Data, see sec. 3. |
| eB | Feedstock conversion | (eB1+eB2-eB3) |
| eB1 | Feedstock use (*ηF* = GJ intermediate per GJ feedstock) | Data, see sec. 4 |
| eB2 | Process energy use (per GJ feedstock) | Data, see sec. 4 |
| eB3 | By-product emissions substituted | eB3a + eB3b |
| eB3a | By-product substituted emissions (per GJ feedstock) | Data, see sec. 4 |
| eB3b | By-product share of emissions (=share of prod. value) | Data, see sec. 4 |
| eC | Total emissions after conversion (per GJ intermediate) | ( eA + eB ) / *ηF* |

A similar calculation is made for the economics of the feedstock conversion technologies, c.f. Table 6.

Table 7 Handling of costs in feedstock conversion

|  |  |  |
| --- | --- | --- |
| **Step** | **Costs** | **Formula** |
| cB | Feedstock conversion (DKK/GJ) | cB1+cB2-cB3+cB4+cB5 |
| cB1 | Feedstock costs | Data, see sec. 3 |
| cB2 | Process energy costs | Data, see sec. 3 |
| cB3 | Income from by-products | Data, see sec. 3 and 4.1 |
| cB3 | Capital costs | Data, see sec. 4 |
| cB4 | Operations and maintenance costs | Data, see sec. 4 |
| cC | Intermediate product (DKK/GJ) | cB / *ηF* |

Finally, the AD model also calculates the energy efficiency of the various parts of the pathway conversion processes.

Table 8 Handling of energy use and efficiency in feedstock conversion

|  |  |  |
| --- | --- | --- |
| **Step** | **Energy use** | **Formula** |
| uA | Process energy use for feedstock | Data, see sec. 3 |
| uB | Conversion energy use (per GJ feedstock) | uB1+uB2-uB3 |
| uB1 | Feedstock use (per GJ feedstock) | 1 |
| uB2 | Process energy use for conversion | Data, see sec. 4.1 |
| uB3 | Energy content of by-products | Data, see sec. 3 and 4.1 |
| uC | Energy use after conversion | (uA + uB ) / *ηF* |

The process energy use, uB2, is also the basis for the calculation of emissions of CH4, N2O, SO₂, NOX and particles which are summed up with the same method as emissions of CO₂.

# Transmission of intermediaries

The transmission of intermediaries covers grid based energy such as electricity and natural gas. For electricity, a transmission loss is assumed while natural gas has a transmission process energy use for compressing the natural gas to the relevant pressure in the gas transmission grid. The methodology for calculating total emissions of the intermediary after transmission is shown in Table 8.

Table 9 Handling of emissions in the transmission step

|  |  |  |
| --- | --- | --- |
| **Step** | **Emission** | **Formula** |
| eD | Intermediary, kg/GJ | eD1+eD2 |
| eD1 | Intermediary before transmission kg/GJ | eC (see Table 5) |
| eD2 | Process energy use GJ/GJ intermediary | Data: CONCAWE (2011) |
| eE | Intermediary after transmission, kg/GJ | eD / *ηT* |

The electricity transmission loss, *ηT*, is based on DEA (2012) section 4.1., and the process energy use is based on CONCAWE (2011).

The cost of transmission is based on data from DEA (2012) table 5. The methodology for calculating intermediary cost after transmission is illustrated in Table 9.

Table 10 Handling of costs of transmission

|  |  |  |
| --- | --- | --- |
| **Step** | **Cost** | **Formula** |
| cD | Intermediary | cD1 + cD2 x *ηT* |
| cD1 | Intermediary before transmission, DKK/GJ | cC (see Table 7) |
| cD2 | Intermediary transmission, DKK/GJ | DEA (2012) |
| cE | Intermediary after transmission, DKK/GJ | cD / *ηT* |

The methodology of energy use and efficiency during transmission is illustrated in Table 10.

Table 11 Handling of energy use and efficiency in transmission

|  |  |  |
| --- | --- | --- |
| **Step** | **Energy use** | **Formula** |
| uD | Intermediary | uD1 + uD2 x *ηT* |
| uD1 | Intermediary before transmission, GJ/GJ | 1 |
| uD2 | Intermediary transmission energy, GJ/GJ | DEA (2012) |
| uE | Intermediary after transmission, GJ/GJ | uD / *ηT* |

The process energy use, uD2, is also the basis for the calculation of emissions of CH4, N2O, SO₂, NOX and particles which are summed up with the same method as emissions of CO₂.

# Intermediate conversion

In some processes, the fuel is converted in two steps:

* a feedstock conversion to intermediates
* an intermediate conversion to fuels

In this section, we describe the intermediate conversion processes used in the AD model.

## Data

The intermediate conversion steps used for fuels and their data sources is showed in Table 11.

Table 12 Fuels with intermediate conversion step

|  |  |  |  |
| --- | --- | --- | --- |
| **Fuel** | **Feedstock conversion** | **Intermediate conversion** | **Data** |
| CNG | Natural gas refining / Biogas | CNG (compression) | CONCAWE (2006) |
| LNG | Natural gas refining | LNG (liquefaction) | CONCAWE (2011) |
| Methanol | Electricity to industry | ETL (emissions to liquid) | FORCE (2013), no. 2 |
| Hydrogen | Electricity to industry | Electrolysis and compression of H2 | CONCAWE (2006) |
| Electricity (cars) | Electricity for homes | Electric car recharging station | COWI / DEA |
| Electricity (trains) | Electricity for industry | Electricity transmission to train | COWI / DEA |

## Methodology

The handling of emission calculation is very similar to that of the feedstock conversion and is described in Table 12.

Table 13 Handling of emission in feedstock conversion

|  |  |  |
| --- | --- | --- |
| **Step** | **Emissions** | **Formula** |
| eF | Intermediate conversion | (eF1+eF2-eF3) |
| eF1 | Intermediate use | 1 |
| eF2 | Process energy use (per GJ feedstock) | Data, see sec. 6.1 |
| eF3 | By-product emissions substituted | eF3a + eF3b |
| eF3a | By-product substituted emissions | Data, see sec. 4, 6.1 |
| eF3b | By-product share of emissions | Data, see sec. 4, 6.1 |
| eG | Total emissions after conversion (per GJ fuel) | eF / *ηF* |

Note: *ηI* = GJ fuel per GJ intermediate

A similar calculation is made for the economics of the intermediate conversion technologies, c.f. Table 13.

Table 14 Handling of costs in feedstock conversion

|  |  |  |
| --- | --- | --- |
| **Step** | **Costs** | **Formula** |
| cF | Intermediate conversion (DKK/GJ intm.) | cF1+cF2-cF3+cF4+cF5 |
| cF1 | Intermediate costs | Data, see sec. 3 |
| cF2 | Process energy costs | Data, see sec. 3 |
| cF3 | Income from by-products | Data, see sec. 3 and 6.1 |
| cF3 | Capital costs | Data, see sec. 4 |
| cF4 | Operations and maintenance costs | Data, see sec. 4 |
| cG | Fuel (DKK/GJ fuel) | cF / *ηF* |

Finally, the AD model also calculates the energy efficiency of the various parts of the pathway conversion processes c.f. Table 14.

Table 15 Handling of energy use and efficiency in intermediate conversion

|  |  |  |
| --- | --- | --- |
| **Step** | **Energy use** | **Formula** |
| uF | Conversion energy use (per GJ intermediate) | uF1+uF2-uF3 |
| uF1 | Intermediate use (per GJ intermediate) | 1 |
| uF2 | Process energy use for conversion | Data, see sec. 4.1 |
| uF3 | Energy content of by-products | Data, see sec. 3 and 4.1 |
| uG | Energy use after intermediate conversion | uF / *ηF* |

The process energy use, uF2, is also the basis for the calculation of emissions of CH4, N2O, SO₂, NOX and particles which are summed up with the same method as emissions of CO₂.

# Distribution of fuel

The process energy use, emissions, loss and costs for distribution of fuels covers the transport and resale activities when the finished fuel leaves the intermediate conversion facility. This step is only relevant for all liquid fuels since the transport of gas and compression happens in the transmission layer of the model

The point of departure for the distribution costs is the cost of gasoline distribution as calculated by DEA (2012). For both tanker trucks and gasoline station volume in cubic metres is the cost driving factor. Therefore, the of distribution of 1 m³ of fuel is assumed to be the same. However, since energy densities of the alternative fuels vary, the distribution cost is scaled using the ratio between the energy density of gasoline and the alternative liquid fuel. The difference can be significant since the energy density of e.g. DME, methanol and ethanol are between half and 2/3 of gasoline. For emissions and energy use, the assumption is a an 18 m³ truck driving 60 km incl. return at a vehicle energy use of 3 km/l using an EURO6 engine.

Alternative fuels for aviation and ships are assumed to have same distribution costs as their fossil equivalents.

The methodology is illustrated in Table 15, Table 16 and Table 17.

Table 16 Handling of emissions in the distribution step

|  |  |  |
| --- | --- | --- |
| **Step** | **Emission** | **Formula** |
| eH | Fuel after distribution, kg/GJ | eH1+eH2 |
| eH1 | Fuel before distribution kg/GJ | eG (see Table 12) |
| eH2 | Process energy use kg/GJ fuel | Data: COWI |

Table 17 Handling of costs of distribution

|  |  |  |
| --- | --- | --- |
| **Step** | **Cost** | **Formula** |
| cH | Fuel after distribution | cH1 + cH2 |
| cH1 | Fuel before distribution, DKK/GJ | cG (see Table 13) |
| cH2 | Fuel distribution, DKK/GJ | DEA (2012) |

The methodology of energy use and efficiency during transmission is illustrated in Table 10.

Table 18 Handling of energy use and efficiency in distribution

|  |  |  |
| --- | --- | --- |
| **Step** | **Energy use** | **Formula** |
| uH | Fuel after distribution | uH1 + uH2 |
| uH1 | Fuel before distribution, GJ/GJ | 1 |
| uH2 | Fuel distribution, GJ/GJ fuel | COWI |

The process energy use, uH2, is also the basis for the calculation of emissions of CH4, N2O, SO₂, NOX and particles which are summed up with the same method as emissions of CO₂.

# Motor conversion technologies

The AD model contains a number of different motor conversion technologies, which transforms fuel to various transport services. The technologies are listed in Table 19.

Table 19 Motor conversion technologies in the AD model

|  |  |  |  |
| --- | --- | --- | --- |
| **Cars** | **Heavy vehicles** | **Trains** | **Ships & aircraft** |
| Gasoline | Truck, diesel | IC diesel | 9000 TEU HFO |
| Diesel | Truck, DME | IC Electric | 9000 TEU diesel |
| Diesel w.DME | Truck, RME | Local diesel | 9000 TEU LNG |
| Otto engine | Truck, Gas | Local gas | Katamaran ferry |
| H2 fuel cell hybrid | Bus, diesel |  |  |
| MeOH fuel cell hybrid | Bus, gas |  |  |
| Plugin hybrid | Bus, hybrid |  |  |
| Electric motor |  |  | Avg. passenger |

## Data

The data for the motor conversion technologies are based on several sources:

* **Cars:** The data on costs are based on CONCAWE (2006), while the data on energy use and conversion efficiency are based on CONCAWE (2014)
* **Trucks and busses:** All data are based on COWI (2014)
* **Trains:** All data have been collected during this project using an external expert on the economics and energy efficiency on trains
* **Ships:** All data have been collected during this project using an external expert on the economics and energy efficiency on trains
* **Aircrafts:** All data have been collected during this project

Further, it is assumed that cars have a usage of 18.000 km/year, while trucks and busses are used for 50.000 km/year. The container ships are assumed to spend 63% of the time at sea. The corresponding usage in km's then depends on their speed, which varies from 22 knots in 2010 to 18 knots in 2035 and 2050. Trains are assumed to travel 250.000 km/year (electric) or 300.000 km/year (diesel and gas). The aircraft data is based on unit costs per km, so no assumptions of total distance travelled was necessary.

### Data for trains

The technical data for trains is based on existing train sets in operation in Denmark. This includes the IC3 (diesel) and IR4 (electric version of IC3) and the Lint41 local train. The technical data is publicly available on dsb.dk and lokalbanen.dk. Financial data is based on a benchmarking study CMC (2012), and Niras (2011).

The technical data is specific for the trains in the model, while the financial data is more general.

### Data for ships

The technical data for the container ships is based on the Excel model of container ship design – Ship-DESMO-Container Ship – designed by Hans-Otto Kristensen at the Danish Shipowners' Association. Data for the katamaran fast ferry is derived from magazine article clippings on 9 katamaran ferries from the magazine Fast Ferry International. Financial data has been derived from Martin Stopford (2009).

The technical data is specific for the ships in the model, while the financial data is more general.

### Data for aircrafts

The data on aircrafts are grossly simplified, since it fuel for aviation is strictly standardised. Industry experts assess that it is not realistic to test and develop jet engines specifically for biofuels, so the biofuels will have to conform to the ordinary jet fuel standards. This means that biofuel for aviation purposes will always be appropriate for conventional jet engines. Therefore, the engine is not a cause of differences in costs, efficiency or emissions between fossil and bio fuels.

Consequently, the data on jet aircraft cost and fuel consumption is a simple average over the Danish aircraft carrier SAS' fleet as stated by their publicly available financial and environmental accounts.

## Methodology

The methodology for computing traffic work emissions and cost is described in Table 20, Table 21 and Table 22.

Table 20 Handling of emissions in the motor conversion step

|  |  |  |
| --- | --- | --- |
| **Step** | **Emission** | **Formula** |
| eI | Emission per traffic work g/km | eI1 x eI2 / eI3 |
| eI1 | Fuel, kg/GJ | See section 7 |
| eI2 | Energy use GJ mechanical/km | Data, see section 8.1 |
| eI3 | Conversion efficiency GJ mechanical/GJ fuel | Data, see section 8.1 |

Table 21 Handling of costs vehicle

|  |  |  |
| --- | --- | --- |
| **Step** | **Cost** | **Formula** |
| cI | Traffic cost, DKK/km | cI1 x eI2 / eI3 + cI2 + cI3 / cI4 |
| cI1 | Fuel costs, DKK/GJ | See section 7 |
| cI2 | O&M costs DKK/km | Data, see section 8.1 |
| cI3 | Vehicle depreciation DKK/year | Data, see section 8.1 |
| cI4 | Vehicle traffic work km/year | Data, see section 8.1 |
| cI5 | Environmental costs | eI + other emissions and noise |

Table 22 Handling of energy use and efficiency in transmission

|  |  |  |
| --- | --- | --- |
| **Step** | **Energy use** | **Formula** |
| uI |  | uH / eI3 |
| uI1 | Fuel before distribution | See uH in Table 18 |

The emission from the vehicle (tank-to-tailpipe) is calculated in two parts: The first part is motor specific, e.g. CH4 from leaks, or NOX stemming from the compression level in the engine. The second part is fuel specific, e.g. fossil CO₂ or particles and SO₂ stemming from the sulphur content of the fuel.

### Hybrid motors

Hybrid motors cover a range of vehicles that use more than one fuel. Typically hybrids combine a conventional fuel with an electric motor. This can be achieved in several ways:

* Hybrid Electric Vehicle (HEV): Primarily Internal Combustion Engine (ICE) supported by an electric engine on acceleration. This vehicle is basically an ICE vehicle with improved efficiency.
* Plugin Hybrid Electric Vehicle (PHEV): Electric and ICE propulsion. Not used in the AD model.
* Range Extender Electric Vehicle (REEV): Full electric propulsion. The ICE or Fuel Cell (FC) will charge the battery on longer trips to "extend the range". **All the plug in hybrids in the AD model are of the range extender type.**

In the AD model, all vehicle data sheets offer the option for energy consumption from two different fuels (primary and secondary) as well as separate engine efficiencies. For vehicles which only use one fuel, energy consumption and engine efficiency need only be specified for the primary fuel.

In some cases energy consumption for hybrid vehicles is only listed as an aggregate. This is not optimal, but it may be applied in the same manner as for the single fuel car with the one exception that the engine efficiency (even though it will be the same value) MUST be specified for both fuels.

In addition to the data on the vehicle data sheets, one more alteration is necessary to make hybrids work. In the "Vehicles" sheet rows 11 and 12 it is possible to indicate a fuel mix. In these rows the energy consumption of each fuel relative to the total energy consumption per km is specified. This kind of data is not always readily available, but it is nonetheless essential. The use of fuel mixes is elaborated below.

### Fuel mixes

The AD model provides a fairly straightforward way to model fuel mixes. In the "Vehicles" sheet rows 11 and 12 it is possible to indicate a fuel mix as the relative energy content of the individual fuels.

The E85 ethanol mix is currently the only fuel mix utilized in the model. E85 indicates that 85% of the volume of the fuel is Ethanol – the rest is gasoline. As ethanol has a lower energy content per volumetric unit, the relative content of energy from the two fuels will not be 85/15. Measured in energy content, the mix is 79/21 – 79% of the energy content of the fuel comes from ethanol.

Another use for the fuel mix option is when the vehicles use more than one fuel, i.e. hybrid vehicles. In that case, the fuel mix indicates the energy consumption of each fuel relative to the total energy consumption per km.

# Modelled pathways

In the AD model, 22 pathways for road transport are modelled, cf. Table 18. The pathways are divided into four groups according to the transport service rendered by the pathway. E.g. spark engine type cars typically have a shorter annual distance and driving pattern than compression engine cars. This means that the pathways can only be compared meaningfully within their own group but not across.

Table 20 Overview of modelled road transport pathways

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  | **Feedstock** | **Conversion** | **Motor** |
| *Cars for shorter trips* | |  |  |  |
|  | Conv. gasoline | Crude oil | Refinery | Spark |
|  | E85 1. Gen. | Wheat | Fermentation | Spark |
|  | E85 1. Gen | Sugar beet | Fermentation | Spark |
|  | E85 2. Gen. | Straw | Fermentation | Spark |
|  | Electric vehicle | Electricity | None | Electric |
|  | Plug-in hybrid | Elec./gasoline | Refinery | Spark hybrid |
| *Cars for longer trips* | |  |  |  |
|  | Conv. diesel | Crude oil | Refinery | Compression |
|  | RME | Rapeseed | Transesterification | Compression |
|  | DME | Wood chips | Syngas route | Compression |
|  | Compressed natural gas | Natural gas | None | Spark |
|  | Compressed biogas | Manure | Fermentation | Spark |
|  | MeOH plug-in hybrid | Wood chips | Syngas route | Fuel cell hybrid |
|  | Hydrogen plug-in hybrid | Electricity | Electrolysis | Fuel cell hybrid |
|  | 2. Gen biodiesel | Straw | Syngas route | Compression |
| *Trucks, regional transport* | |  |  |  |
|  | Conv. diesel | Crude oil | Refinery | Compression |
|  | RME | Rapeseed | Oil seed press | Compression |
|  | DME | Wood chips | Syngas route | Compression |
|  | Compressed natural gas | Natural gas | None | Spark |
| *Busses* | |  |  |  |
|  | Diesel | Crude oil | Refinery | Compression |
|  | RME | Rapeseed | Transesterification | Compression |
|  | Compressed natural gas | Natural gas | None | Spark |
|  | Hybrid diesel | Crude oil | Refinery | Compression / hybrid |

Further, 13 pathways for other transport needs are also modelled, c.f. Table 19.

Table 21 Overview of modelled other transport pathways

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  | **Feedstock** | **Conversion** | **Motor** |
| *Regional trains* | |  |  |  |
|  | Conv. diesel | Crude oil | Refinery | Diesel-electric |
|  | 2. Gen. biodiesel | Straw | Syngas route | Diesel-electric |
|  | Compressed natural gas | Natural gas | None | Dual fuel? |
| *Intercity trains* | |  |  |  |
|  | Conv. diesel | Crude oil | Refinery | Diesel-electric |
|  | 2. Gen. biodiesel | Straw | Syngas route | Diesel-electric |
|  | Electric | Electricity |  | Electric |
| *Ships* | |  |  |  |
|  | Fast ferry, diesel | Crude oil | Refinery | Gas turbine |
|  | 9000 TEU HFO | Crude oil | Refinery | Compression |
|  | 9000 TEU diesel | Crude oil | Refinery | Compression |
|  | 9000 TEU biodiesel | Straw | Syngas route | Compression |
|  | 9000 TEU LNG | Natural gas | Liquefaction | Dual fuel |
| *Aircrafts* | |  |  |  |
|  | Jet petroleum | Crude oil | Refinery | Jet engine |
|  | Bio jet petroleum | Straw | Syngas route | Jet engine |

Even within the grouping presented above, the pathways are not fully comparable, e.g. electric trans are capable of delivering better acceleration and thereby faster travel. Further, some liquid fuels have lower density than others and are thus less ideal for long range transport because of the additional fuel weight or higher number of refuelling stops.

# Technological development

The handling of technological development and reductions in cost follows the "learning curve" approach as described in FORCE (2013), chapter 7. According to this approach, "(s)uch a learning curve basically assumes that each time the accumulated production is doubled, the production cost I reduced by a certain factor, typically in the order of 5 to 15 %."

Further, FORCE (2013) recommends a learning ratio of 95 % for capital expenses, meaning that after a doubling of the cumulated world capacity of a specific type of plant, the cost of producing the next plant is only 95 % of the original cost as stated by the data. A quadrupling of world capacities would thus result in a capacity cost of 95% ^ 4 = 81.5%.

In order to accommodate different learning outcomes in the AD model, it is possible for the user to select between three learning patterns specifying the cumulated world capacity:

* **None:** There is no learning and reduction of capital costs
* **Moderate:** Learning is set according to a moderate development in accumulated world capacity
* **Fast:** Learning is set according to a moderate development in accumulated world capacity

It has been outside the scope of this project to determine actual values to use in the learning curve calculation. COWI has provided examples for the three groups split on four types of technologies according to how new they are:

* **Established:** Technologies which has been used for several decades, e.g. fossil refineries. These have no learning
* **Recent:** Technologies which has been used for around one or two decades, e.g. 1G ethanol on wheat, RME, biogas.
* **New:** Technologies which has been used for less than a decade, e.g. 1G ethanol on sugar beets, 2G ethanol on straw, MeOH (syngas route).
* **Developing:** Technologies which is just becoming available, e.g. DME, bio jet fuel, MeOH (ETL)

In the AD model some illustrative, very rough and tentative suggestions for learning patterns through world cumulated production capacity are provided in the time period between 2010 and 2050. It is suggested that the world capacity relevant for learning might increase with a factor 2-8 for recent technologies, a factor 3 to 12 for new technologies and a factor 4-16 for developing technologies. In other words, in the best case capital costs for the most recent technologies may decrease to 95%^16 = 45% of the cost stated in FORCE (2013).

We must stress that these factors are merely loosely founded suggestions only fit for "what-if" sensitivity analyses, and not actual estimates for the expected development. The model user is strongly encouraged to investigate the expected learning of specific technologies in case this topic is central to the user's analyses with the AD model.

# Model interface

## Presentation of results

### Cockpit

In the sheet called "Cockpit" a number of charts show the socio-economic costs, emissions and system efficiency of the different pathways grouped by cars, trucks/busses, ships aircrafts and trains. A number of dropdown boxes allow the user to

* Change the year between 2010, 2020, 2035 and 2050
* Change between various ILUC assumptions
* Change whether emissions of allowance market CO₂ is accounted as an emission or an allowance cost
* Change learning assumptions between None, Moderate and Fast
* Select a specific sensitivity scenario

### ResultsAllYears

In the sheet "ResultsAllYears", the users can see consolidated charts for one group of vehicle types. The charts also show the development in costs and emissions over time.

The user can decide which pathways that are presented in the chart by assigning each pathway a letter (A to F) in the "Chart control table". Then selecting which group to show in the dropdown menu and pressing the button "Update charts" will update the charts to the user's selection.

### A4results

In the sheet "A4 results", the user can view very specific details for one pathway. This sheet is printable in an easily readable A4 paper format. It shows all four years (2010, 2020, 2035 and 2050) in four columns as well as 3 columns for selected sensitivity analyses.

Located in cell V1 there is a dropdown menu where the user can select which pathway to view. After selecting a pathway, the button "Update tables" must be pressed. Then, the table will be update its columns with the years specified by the table "Year selection", and the sensitivity scenarios specified by the table "Sensitivity selection" (both with left corners in column V).

### Sensitivity

The sheet sensitivity allow the user to make sensitivity analyses targeted towards specific groups of pathways. Groups of pathways can be defined in the table called "Definition of vehicles groups for sensitivity analysis".

In the table called "Combination of sensitivity scenarios (rows) and sensitivity parameters (columns)" the user can define 5 sensitivity analyses for each group by writing the group name label in column D and adjusting the sensitivity settings in column F to S. It is possible to combine several sensitivity parameters in one sensitivity scenario (a row in the table), or just to adjust on one sensitivity variable only.

After adjusting the sensitivity scenarios and groups (or after making other changes to the model) the sensitivity analyses can be re-run by pressing the button "Update sensitivity tables & charts".

### Log

The AD model also offers a logging functionality, where the user can log and explain differences due to changes in the model or assumptions. This can be done in the sheet "Log2010". In this sheet and the sheets Log2020, Log2035 and Log2050 already logged changes can be seen.

If an assumption or calculation method is updated, the results on economic, emissions and efficiency will typically change. The results last logged by the user will be compared to the current results and any difference will be highlighted with colours. Differences are also written in white text in row 1 on many of the sheets in the model. This allows the user quickly to be aware if intended or unintended changes in the model affect the results.

The user is encouraged log any change by writing the reason for the changes in cell K5 alongside with his name/initials/email address in cell K4 and then press the button named "Log results". Then the present results will be copied to the bottom of the log alongside the reason, initial and date. This feature is highly useful for tracking changes and their reasoning, but will only work if the user assert some discipline in logging any change as soon as it occur.

## Adding new technologies and pathways

The calculation of a pathway happens in two successive steps: First the fuel and the vehicle.

### Adding vehicles

It is possible for a vehicle to use the same fuel as other vehicles, so new pathways can be added just by adding vehicles.

1. In the sheet "Vehicles" insert a new column between two existing columns or change an existing column to match your new pathway.
2. Add a new pathway label (not identical to any other pathway label) in row 6
3. Add label for primary and secondary fuel (if any) in row 6 and 7. The label must be a fuel present on the sheet "Fuels".
4. If the vehicle uses dual fuels, set the distribution of primary and secondary fuels in row 10 and 11. The percentages cover energy, not volume or mass. Note that hybrid vehicles (motor + battery) has only one fuel here, and that the split between battery and motor propelling is handled on the relevant motor technology sheet

### Adding conversion technologies

It is possible for a user to add new conversion technologies and fuels to the model. Data for conversion technologies are stored on the light blue data sheets. The new fuels can be added by following the steps described below.

1. In the sheet "Fuels" find an empty column or add a new column between two existing fuels.
2. Enter the name of the new fuel (row 6) and the category for tailpipe emissions (row 7), and the feedstock (row 8)
3. Enter the category of transport between feedstock and intermediate conversion (row 9) and the category of distribution (row 10)
4. Enter the sheet name of the feedstock conversion technology in row 11, and the sheet name of the intermediate conversion technology in row 12. These sheet names must also be present (to be added by hand) in column I on the sheet "Supplementary" after row 267.

References

The following references are used in this document. For a full list of data sources used for the entire AD model, see the spreadsheet page called "References".

Concawe (2006): *Well-to-wheels analysis of future automotive fuels and powertrains in the European Context*. May 2006.

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Overview of pathway cost and emissions

 





 









1. This was agreed with DEA in a correspondance 8 Dec 2011. [↑](#footnote-ref-1)
2. While only few oil refineries enjoy a true monopoly, the economics of scale in the sector justifies some sort of local market power. Therefore, the producers can expect that their quantity decisions does influence the local market prices. This is captured by the unspecified demand functions P1 and P2 which could be thought to capture the residual demand of the refinery. [↑](#footnote-ref-2)