Ea Energy Analyses
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Working paper

Fuel costs – Production, distribution and infrastructure costs used in the Economic Analysis in Grøn Roadmap 2030

The current paper describes the assumptions undertaken, data utilised, and overall methodology, in calculating the costs associated with the production, transmission and distribution of fuels to end users for various vehicle types. The analysis takes a socioeconomic approach (i.e. costs without taxes, utilises the socioeconomic discount rate prescribed by the Danish Ministry of Finance, etc.), although some aspects of a stringent socio-economic analysis (i.e. some wider implications such as spill over effects) are not included. All costs are in 2015 DKK.

The fuels described are:

- Gasoline
- Diesel
- Natural Gas
- Biofuels:
    - Bioethanol – 1st generation
    - Bioethanol – 2nd generation
    - Biodiesel – 1st generation
    - Biodiesel – 2nd generation
    - HVO – 1st generation
    - HVO – 2nd generation
- Biogas
- Electricity
- Hydrogen

For each of the above fuels, the value chain was divided into **the production cost ex. refinery/plant** (or import location if relevant), **transmission & distribution cost**, and if applicable, the additional **infrastructure cost**. Where relevant, different transmission & distribution and infrastructure costs were calculated according to the four general vehicle categories:

- Personal vehicles
- Light Duty Vehicles (LDVs)
- Heavy Duty Vehicles (HDVs)
- Busses

In addition to the above fuels and technologies, an initial screening was undertaken that also considered alternative fuels (including methanol, DME, etc.), as well as some of the above fuels for use in some of the existing vehicle categories (hydrogen or electricity in HDVs for example). Based on considerations regarding their future technological development and/or cost, some fuels and technological options were not included in the selected scenarios, and these are not described in detail here.

Fuel production costs

Gasoline, diesel and natural gas

Gasoline, diesel and natural gas production costs are those that Ea Energy Analyses have provided to the Danish Energy Agency (DEA) and include future forecasted prices based on: IEA's World Energy Outlook prices, a price adjustment that takes into account the historic difference between the IEA prices and those realised in Demark, and a convergence in the near term between IEA's long term price forecasts and the forward prices currently seen in the market today. Documents with these figures, and a thorough description of the methodology employed can be found on the Danish Energy Agency's website.[1]

Biofuels – production cost

An extensive literature review revealed that there is a wide range in production cost estimates for the biofuels in focus in the current analysis. In order to arrive at production costs for each biofuel towards 2030, simple excel models for four of the six biofuels (1st and 2nd generation bioethanol, 1st generation biodiesel, and 1st generation HVO) were therefore developed. For the remaining two (2nd generation HVO and biodiesel – which had very limited usage volumes in the scenarios[2]), price assumptions in relation to the other biofuels were made.

[1] http://www.ens.dk/info/tal-kort/fremskrivninger-analyser-modeller/samfundsokonomiske-beregnings-forudsaetninger

[2] 2nd generation HVO is not utilised during the study period, while a relatively small amount of 2nd generation biodiesel is introduced in later years.

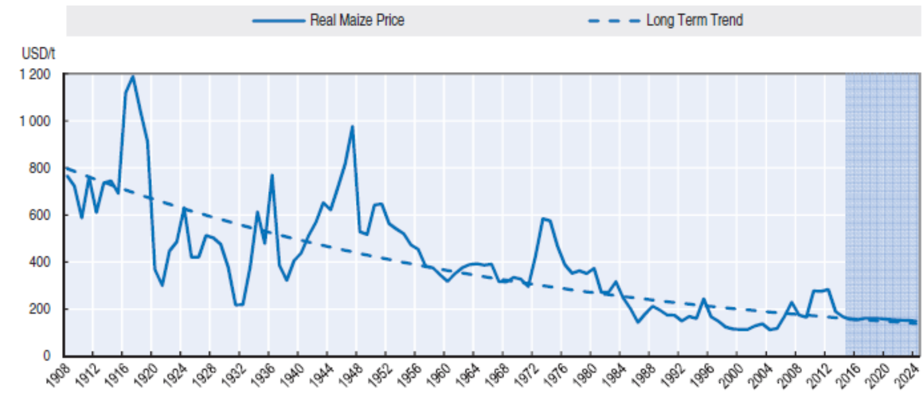
Bioethanol – 1st generation

First generation bioethanol production is a well-known and mature technology. Today, the majority of global bioethanol is produced in the United States (corn based) and in Brazil (primarily sugar based). In Europe meanwhile, the main crop for bioethanol production is wheat. Though production costs are lower in the United states (partially due to subsides) and Brazil (partially due to subsidies, but also due to Brazil's efficient sugarcane production and bagasse by-product that also generates revenue), significant EU import duties raise these prices, thus allowing European producers to be competitive. In the current study, the production cost for 1st generation bioethanol is therefore based on bioethanol produced from wheat in Europe.

Wheat cost all important

By far the most important price component is the cost of wheat. A 2014 study carried out by the Australian government (Bureau of Resources and Energy Economics , 2014), found that the net cost of production for grain-based bioethanol was roughly 2% higher than the wheat feedstock cost. This was because the revenue generated from the sale of ethanol by-products nearly offset the capital and operating costs of the bioethanol plant.

Current wheat and grain prices have fallen significantly from recent highs seen in 2007 and 2012. According to the Food and Agriculture Organization of the United Nations (FAO), the current low prices are due to successive record harvests in grains and oilseeds, and it is anticipated that prices will increase again in upcoming years. Looking further into the future, FAO forecasts that grain prices will continue their long-term trend, which has seen prices in real terms fall since the start of the 20th century. This is highlighted in the figure below, which displays the price of US yellow #2 Gulf maize, price that is used as a benchmark for the global grain price. (OECD-FAO, 2015).



Note: The US yellow #2 Gulf maize price is used as a benchmark for the coarse grain world market price. This price is recorded back to 1960 in World Bank datasets as monthly data. Monthly prices were converted to annual averages using the maize marketing year September-August. For the years 1908-59 the series is extended using the relative changes in "corn price received" from the USDA quickstats. Nominal prices are deflated using the consumer price as reported by the Federal Bank (*www.minneapolisfed.org/community_education/teacher/calc/hist1800.cfm*).

Figure 1: Price of US yellow #2 Gulf maize in real terms (USD/t) (OECD-FAO, 2015)

Wheat pricing methodology

The wheat pricing methodology in the current study combines the use of forward prices for European feed wheat, with the long term price fall in real terms indicated by FAO. Feed wheat was selected as input as it is cheaper than wheat intended for human consumption, and feed wheat's higher starch and lower protein content are preferable for ethanol production (AHDB, 2010). There are two primary forward contracts for wheat in Europe: the Matif Milling Wheat Contract, which is the benchmark for wheat meant for human consumption, and the Liffe Feed Wheat Contract, which is a benchmark for European feed wheat and is traded in pounds sterling per metric tonne (Commodity Basis, 2015). Forward prices for feed wheat were available up till the end of 2017.

The figure below displays the historic UK feed wheat prices in real terms in both DKK and British £ (Investing.com, 2015). Prices in nominal £ were converted to 2015 £ according to historical United Kingdom CPI data (Rate Inflation, 2015). 2015 £ figures were then converted to 2015 DKK figures given monthly average exchange rates from Denmark's National bank (Danmarks Nationalbank, 2015). Since 1990, the monthly DKK/€ exchange rate has ranged from 8 to 15 DKK/€, and averaged 10.25. For 2015, the monthly average was 10.26 DKK/£, and this is the exchange rate that has been utilised going forward.

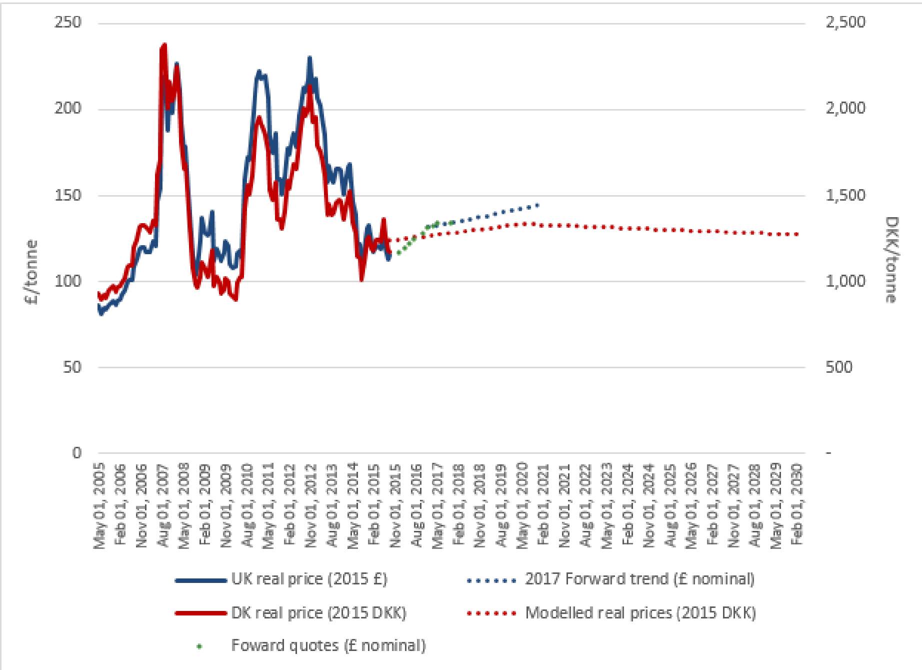


Figure 2: Historical UK feed wheat prices (in real terms), future contracts until the end of 2017 (in nominal terms), and the modelled wheat price development towards 2030 (in real terms).

Both of the above figures illustrate the fact that the price of wheat is quite volatile, and can vary significantly over relatively short time frames. As such, it was determined to use forward contracts as the best estimate for feed wheat prices in the relative short term, in this case up to 2020. Meanwhile, Figure 1 indicates a falling price over the long term, with current prices being below this long term trend due to recent record harvests (OECD-FAO, 2015). Forward prices up to 2017 appear to confirm this, as they indicate moderate price increases in 2016, with this price increase levelling off in 2017. The 2020 price was arrived at by extending the 2017 futures trend through to 2020, and the resulting price is roughly 1340 DKK/tonne (in 2015 DKK). The long term trend depicted in Figure 1 indicates an annual price fall, in real terms, by roughly 0.5% from 2000 to 2020. This annual price reduction was applied to the 2020 figure and maintained towards 2030 giving a price of roughly 1270 DKK/tonne.

Put simply, the wheat pricing methodology could be summarised by the following assumptions:

a) there exists a long-term falling price trend (in real terms), that will continue to 2030,
b) we are currently witnessing prices below this long-term trend,
c) by 2020 it is assumed that prices will have returned to this long-term trend.

Ethanol yield

The other important factor is the ethanol yield per kg of feedstock. The aforementioned Australian study found a yield of 0.38 $litres_{eth}$ /kg_{wht} (equivalent to 2.6 kg of wheat input per litre of ethanol output, which is the same figure quoted by the Swedish ethanol plant in Norrköping (Lantmännen, 2015)). As the process is based on mature technology, the current study forecasts modest gains in this yield from 2015 to 2030.

Resulting costs

Based on the above inputs and assumptions, the table below displays the resulting production costs for 1st generation bioethanol. It should be noted that the number of decimal places in the table *do not* reflect the uncertainty related to the final price. This is particularly due to the uncertainty related to the price of wheat, which as Figure 2 above highlights, can vary significantly.

	2015	2020	2030
Wheat cost (£/tonne) – nominal terms	120	143	166
DKK/£	10.3	10.3	10.3
DKK/AUD	4.8	4.8	4.8
Wheat cost (DKK/kg) – real terms	1.23	1.34	1.27
Transport/storage (% of wheat cost)	10%	10%	10%
Total wheat cost (DKK/kg)	**1.35**	**1.47**	**1.40**
Ethanol yield per kg feedstock (l/kg)	0.38	0.39	0.40
Wheat/litre bioethanol (kg/l)	2.62	2.59	2.52
Feedstock costs (DKK/litre)	3.53	3.80	3.53
Feedstock costs (DKK/GJ)	**167.5**	**180.2**	**167.2**
Non-feedstock operating costs (AUD/litre)	0.19	0.19	0.19
By product revenue (AUD/litre)	0.16	0.16	0.16
Net cost difference - by-products & capital (DKK/litre)	0.14	0.14	0.14
Net cost difference - by-products & capital (DKK/GJ)	**6.8**	**6.8**	**6.8**
Net production cost (DKK/litre)	3.68	3.94	3.67
Net production cost (DKK/GJ)	**174**	**187**	**174**

Table 1: Forecasted 1st generation bioethanol production costs for wheat based ethanol.

Biodiesel – 1st generation

First generation biodiesel production is a well-known and mature technology. As was the case with bioethanol, the United States is currently the largest global producer, but the EU is also a large producer of biodiesel (largely Germany and France), with roughly 40% of 2013 global production (Energy Trends Insider, 2014). Within this study, it is assumed that EU biodiesel is FAME (Fatty acid methyl esters) produced from rapeseed oil.

Rapeseed oil cost all important

For biodiesel the most important cost element is once again the feedstock, as this accounts for roughly 90-95% of the net production cost (IRENA, 2013).

As was the case with wheat, current rapeseed oil prices have fallen significantly from highs seen in 2007 and 2012, and according to the Food and Agriculture Organization of the United Nations (FAO), prices are anticipated to increase by 2020 and 2030 (in nominal terms), but still be well below those seen in 2012. (OECD-FAO, 2015). While wheat futures indicate rising prices in the upcoming years, rapeseed futures[3] point to a market that will continue to be in over-supply for a longer period (see green dots in Figure 3 below). These

[3] The traded volume for Matif-Rapeseed futures is higher than that for rapeseed oil, and has therefore been used as proxy for future rapeseed oil (ZMP, 2015).

futures indicate a market where prices will continue to fall throughout 2016 and 2017 before starting to increase in 2018.

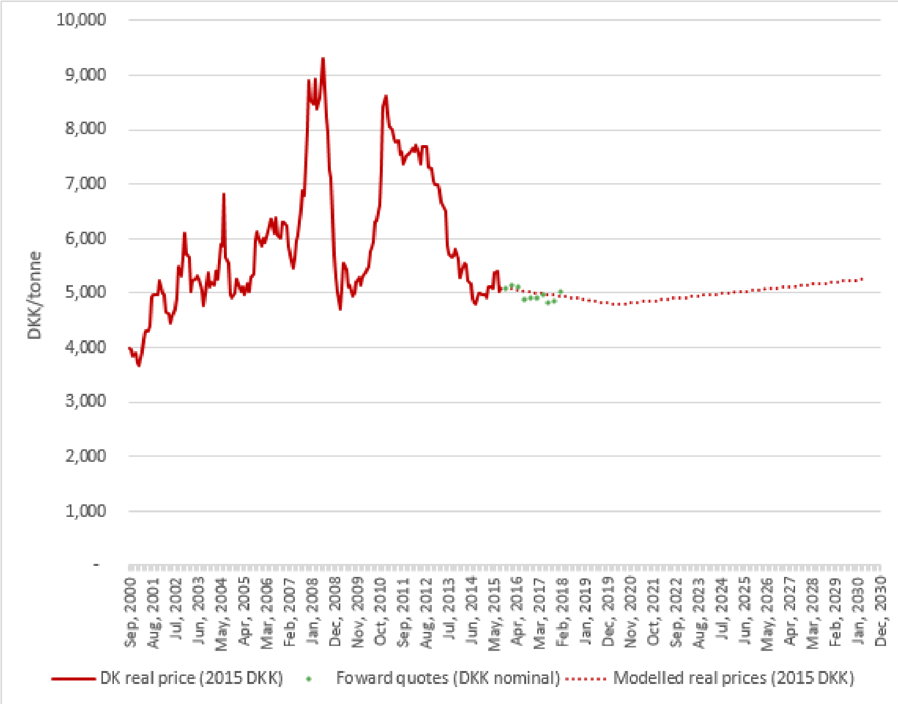


Figure 3: Historical European rapeseed oil prices (in real terms), future contracts until the end of 2017 (in nominal terms), and the modelled rapeseed oil price development towards 2030 (in real terms).

The 2020 price was arrived at by extending the 2017 futures trend through to 2020, and the resulting price is roughly 4,800 DKK/tonne (in 2015 DKK). Meanwhile, the 2030 price was again based on FAO's long-term forecast. FAO undertook a stochastic analysis and modelled seed prices till 2024 (see figure below. If this trend is maintained to 2030) this indicates a seed price in nominal terms that is roughly 30% higher than today.

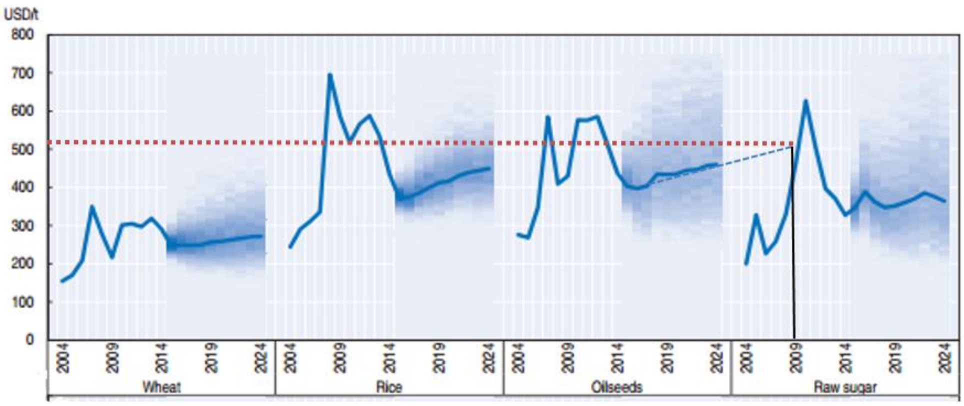


Figure 4: Agricultural price trends in nominal USD/tonne derived from stochastic analyses. Dotted lines have been added (OECD-FAO, 2015).

However, since the FAO report was published, rapeseed forward prices have instead continued to fall further (Figure 3). Taking this into consideration, and once again using rapeseed prices as a proxy for rapeseed oil prices, it was estimated that nominal rapeseed oil prices in 2030 would be roughly 39% higher than 2015 prices. In real terms, this corresponds to a rapeseed oil price of roughly 5,270 DKK in 2030.

Biodiesel yield

In the case of biodiesel, the yield per kg of feedstock was estimated to be 1.09 $litres_{biod}$ /kg_{rs} (IRENA, 2013), equivalent to 0.9 kg of rapeseed oil input per litre of biodiesel output. As biodiesel projection is a well-known and mature technology, the current study forecasts modest only slight gains in this yield from 2015 to 2030.

Based on the above inputs and assumptions, the table below displays the resulting production costs for 1st generation biodiesel. Once again, the number of decimal places in the table *do not* reflect the uncertainty related to the final price.

	2015	2020	2030
Rapeseed oil (€/tonne) – nominal €	680	710	950
DKK/€	7.44	7.44	7.44
Rapeseed cost – real (2015 DKK/kg)	5.1	4.8	5.3
Transport/storage (% of rapeseed cost)	10%	10%	10%
Total rapeseed cost (2015 DKK/kg)	**5.4**	**5.1**	**5.3**
biodiesel yield per kg feedstock (l/kg)	1.09	1.09	1.10
Rapeseed/litre biodiesel (kg/l)	0.9	0.9	0.9
Feedstock costs (DKK/litre)	5.1	4.8	5.3
Feedstock costs (2015 DKK/GJ)	**163**	**153**	**166**
Non-feedstock operating costs (USD/litre)	0.10	0.10	0.10
By product revenue (USD/litre)	0.04	0.04	0.04
Net cost difference - by-products & capital (DKK/litre)	0.42	0.39	0.39
Net cost difference - by-products & capital (DKK/GJ)	**13**	**13**	**13**
Net production cost (DKK/litre)	5.36	5.07	5.25
Net production cost (2015 DKK/GJ)	**176**	**166**	**180**

Table 2: Forecasted 1st generation biodiesel production costs based on European rapeseed oil.

Wheat vs. rapeseed oil forecasts

In comparing the price forecasts for wheat (Figure 2) and rapeseed oil (Figure 3), it may on first glance appear counterintuitive that for wheat there is assumed a small price increase up to 2020, followed by a fall towards 2030, whereas for rapeseed oil, there is instead assumed a slight price fall towards 2020, thereafter followed by minor price increase to 2030. This trend can also be deduced from FAO's forecast (Figure 4), which shows (in nominal terms) slowly increasing prices for wheat, but a price dip followed by moderate prices increases thereafter for oilseeds.

The figure below may help in explaining this. It displays the monthly historic nominal prices of wheat and rapeseed oil in the United States since 2000. During the first 11 years of the period the price of the two commodities were highly correlated, but since 2012, rapeseed oil appears to have fallen more in price relative to wheat. In addition, forward prices indicate that rapeseed oil will continue to fall in price, while wheat prices appear to be increasing. If it is assumed that prices in 2030 will resume the long term trend seen from 2000 to 2011, then it is not unreasonable to foresee a 2020-2030 price evolution involving a slight price fall for wheat, coupled with a slight price increase for rapeseed oil.

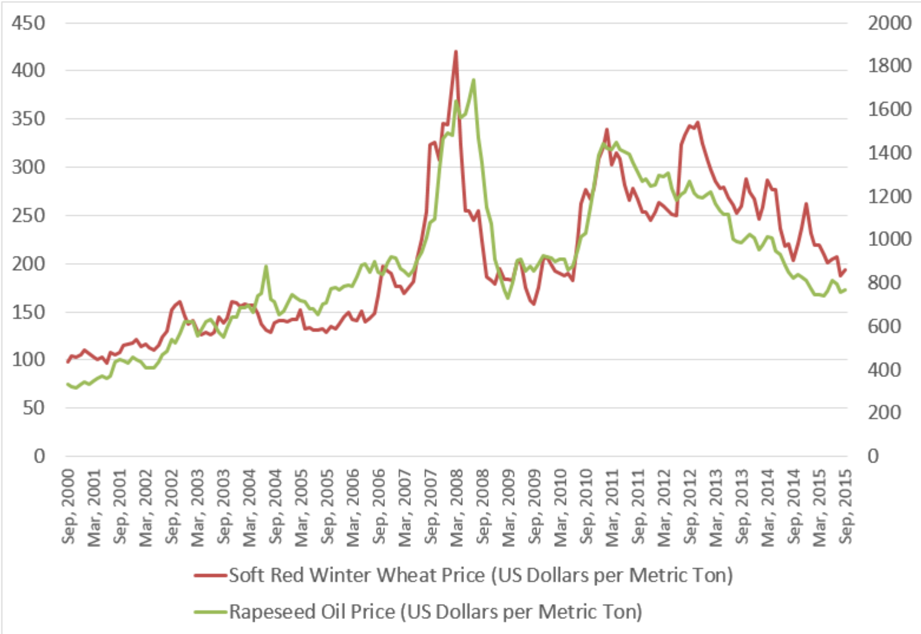


Figure 5: Average monthly nominal prices of wheat and rapeseed oil in the United States since 2000 (Index Mundi, 2015).

HVO – 1st generation

Hydrotreated vegetable oil (HVO) has emerged as an attractive alternative to biodiesel in recent years. It utilises the same feedstocks as 1 G biodiesel, and combines them with hydrogen to produce an end product that is very similar to diesel, thereby allowing it to be easily 'dropped in' to regular diesel. The downside however, is that this hydrotreating process incurs large capital costs and therefore requires large-scale production. (Energy Trends Insider, 2014).

The production costs in this study are based on HVO from rapeseed, and CAPEX, OPEX and plant efficiencies from Force Technology's 2013 report entitled "Technology data for advanced biofuels". (Force Technology, 2013).

			2015	2020	2030
CAPEX					
	Annual production	mio GJ/year	35	35	35
	CAPEX	DKK/GJ HVO	145	145	145
	Total CAPEX	mio. DKK	5,081	5,081	5,081
OPEX					
	D&V	DKK/GJ HVO	4.32	4.32	4.32
Inputs					
	Rapeseed oil use	GJ/GJ diesel	1.04	1.04	1.04
	Rapeseed oil use	mio GJ/year	36.6	36.6	36.6
	Hydrogen use	GJ/GJ diesel	0.09	0.09	0.09
	Hydrogen use	mio GJ/year	3.2	3.2	3.2
Revenues					
	Petrol production	GJ/GJ diesel	0.01	0.01	0.01
	Petrol production	mio GJ/year	0.4	0.4	0.4
	Electricity production	GJ/GJ diesel	0.003	0.003	0.003
	Electricity production	mio GJ/year	0.1	0.1	0.1
	Heat production	GJ/GJ diesel	0.011	0.011	0.011
	Heat production	mio GJ/year	0.4	0.4	0.4
Totals (per year)					
	CAPEX	mio DKK/year	374	374	374
	OPEX	mio DKK/year	152	152	152
	Rapeseed oil	mio DKK/year	5,53	5,225	5,740
	Hydrogen	mio DKK/year	835	835	897
	Total costs	**mio DKK/year**	**6,884**	**6,585**	**7,162**
	Petrol	mio DKK/year	32	35	51
	El	mio DKK/year	18	18	19
	Heat	mio DKK/year	23	23	23
	Total revenues from by-products	**mio DKK/year**	**73**	**76**	**94**
	HVO production cost	**DKK/GJ**	**193**	**185**	**201**

Table 3: Economics for 1st generation HVO. All prices in 2015 DKK.

Bioethanol – 2nd generation

Second generation bioethanol production is not yet a mature technology, and on a global level can best be described as being at the R&D and pilot project phase. One of the largest challenges facing 2 G bioethanol production is that more by-products are produced per tonne of feedstock then the desired bioethanol. As a result, it is important that there is a market for these by-products, and/or the by-products are part of an integrated process involving district heating and/or biogas production.

There has been a good deal of R&D in Denmark, including plans for a full scale plant that is to come online around 2020. Data from this Maabjerg Energy Concept project have been used to calculate the production cost for 2nd generation bioethanol (MEC, 2015).

The table below shows the assumed cost inputs for the 2nd generation bioethanol project. In 2030, it is assumed that less enzymes will be required per litre of ethanol (Klein-Marcuschamer, Oleskowicz-Popiel, Simmons, & Blanch, 2011), and that capital costs will have been reduced.

	2020	2030	Notes/References
Inputs			
Straw (DKK/GJ)*	44	47	(ENS, 2014)
Steam (DKK/GJ)	51	55	Wood chip price (ENS, 2014)
Electricity (DKK/MWh)	250	380	Ea calculations
Enzymes (DKK/l ethanol)	1.6	0.8	(Klein-Marcuschamer, Oleskowicz-Popiel, Simmons, & Blanch, 2011)
Outputs			
Lignin (DKK/GJ)*	51	55	Wood chip price (ENS, 2014)
Vinasse (DKK/tonne)**	600	600	Ea assumption
CAPEX + OPEX			
CAPEX (mio. DKK)	1809	1550	Maabjerg Energy Concept (MEC, 2015)
Lifetime (year)	20	20	Maabjerg Energy Concept (MEC, 2015)
Interest	4%	4%	Ea assumption
OPEX (% of investment)	4%	4%	Ea assumption

*Table 4: 2nd generation bioethanol assumptions – Costs. All prices in 2015 DKK. *Straw - 14.5 GJ/tonne, Lignin - 17.0 GJ/tonne.**Based on the socio-economic value of biogas that the viannsse can be used to produce.*

The next table displays the assumed inputs and outputs of a 2nd generation bioethanol plant in Denmark for the years 2020 and 2030.

	2020	2030	Notes/References
Inputs			
Straw (kilotons)	300	300	Maabjerg Energy Concept (MEC, 2015)
Steam (TJ)	600	600	Maabjerg Energy Concept (MEC, 2015)
El (GWh)	60	60	Maabjerg Energy Concept (MEC, 2015)
Outputs			
Lignin (kilotons)	92	92	Maabjerg Energy Concept (MEC, 2015)
Vinasse (kilotons)	92	92	Maabjerg Energy Concept (MEC, 2015)
Bioethanol (mio. l)	77	77	Maabjerg Energy Concept (MEC, 2015)

Table 5: 2nd generation bioethanol assumptions – Inputs/Outputs

Based on the above two tables, Table 6 shows the overall production costs for 2nd generation bioethanol in Denmark.

		2020	2030
Costs			
CAPEX	mio DKK/year	133	114
D&V	mio DKK/year	72	62
Straw	mio DKK/year	189	203
Steam	mio DKK/year	30	33
El	mio DKK/year	15	23
Enzymes	mio DKK/year	123	61
Diverse	mio DKK/year	17	18
Total	mio DKK/year	580	514
Revenues			
Lignin	mio DKK/year	79	85
Vinasse	mio DKK/year	55	55
Total	mio DKK/year	135	141
Total			
Bioethanol production	TJ	1,624	1,624
Bioethanol production cost	**DKK/GJ**	**274**	**230**

Table 6: Economics for 1st generation bioethanol. All prices in 2015 DKK.

Biodiesel – 2nd generation

Only a relatively small amount of 2nd generation biodiesel is introduced in later years during the scenario period, and therefore a bottom up production cost analysis was not undertaken. Based on interviews with market actors and a literature review, it was determined that 2nd generation biodiesel is likely to have a production cost higher than 1 G biodiesel, but lower than 1 G HVO, with the price likely to be closer to HVO. As such, a simple weighted average production price based on 2/3 HVO, and 1/3 biodiesel was used.

HVO – 2nd generation

Second generation HVO is not utilised in the scenarios prior to 2030, and therefore a bottom up production cost analysis was not undertaken. For the years after 2030, 2 G HVO is assumed to have a production cost roughly 20% higher than 1 G HVO.

Biofuels – price premium

Minimum price premium between gasoline/diesel & biofuels

As a starting point, the study has estimated the cost of producing 1st and 2nd generation bioethanol, biodiesel and HVO as described above. However, due to the fact that these biofuels are RE based, and have a much lower carbon footprint than their fossil counterparts, it is assumed that there will always be a price premium for these biofuels vs gasoline/diesel. For 2nd generation biofuels this RE premium has been set to 15 øre/kWh (similar to the RE premium that electricity from biomass receives), and for 1st generation biofuels the premium is 7.5 øre/kWh. As such, the biofuel price utilised in the scenarios will depend on the gasoline and diesel price utilised in the forecast. I.e., with very high oil prices the biofuel price will likely be set by the CO_2 based premium, while with very low oil prices the biofuel price will be set by the assumed production cost. The figure below displays the resulting fuel production prices utilised in the main scenarios.

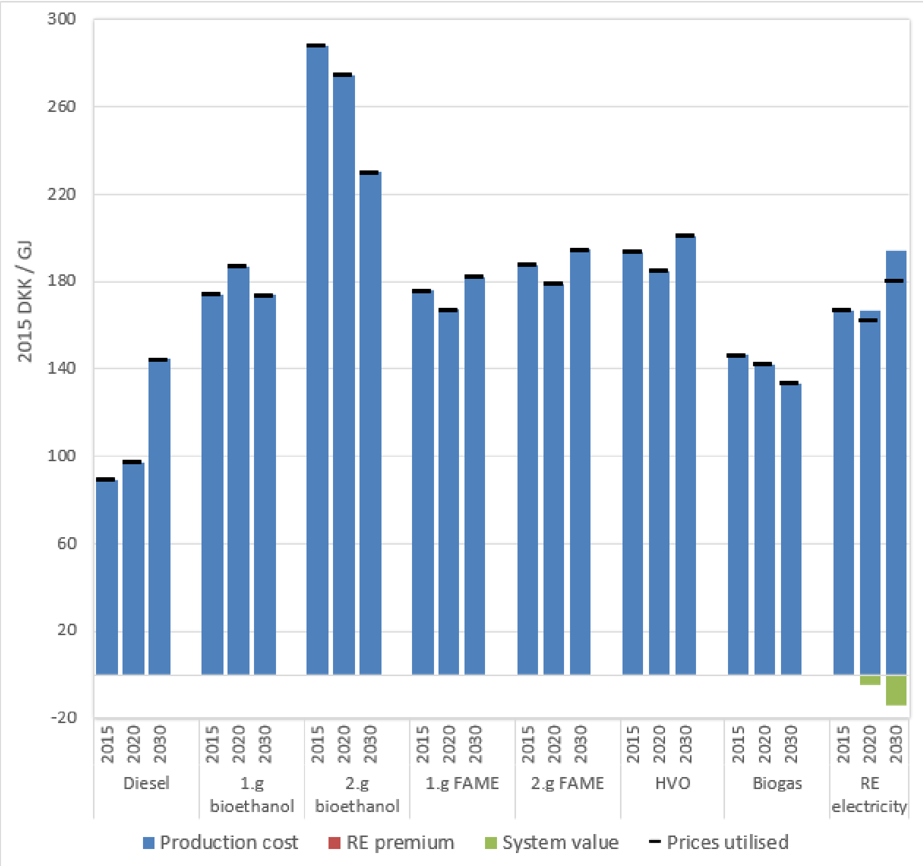


Figure 6: Fuel production prices utilised in the scenarios.

As can be seen in the following figure, in a situation with higher oil prices the effect of the RE premium on the biofuel prices utilised becomes relevant (the red portion of the graph).

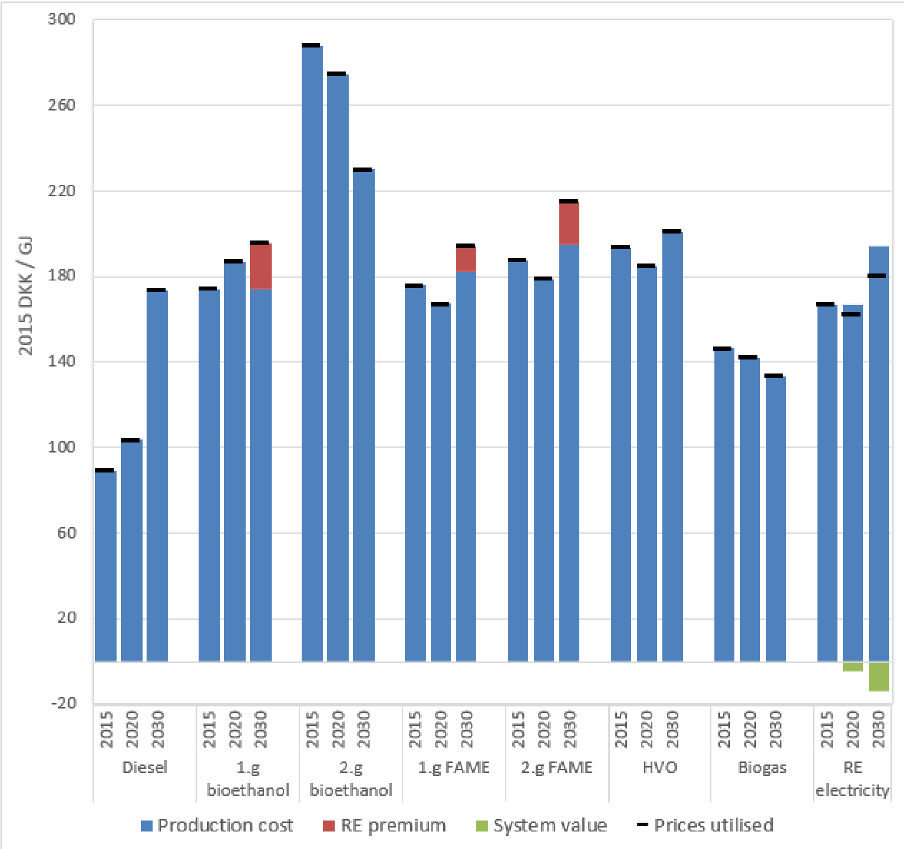


Figure 7: Fuel production prices in a sensitivity analysis with higher oil prices.

Biogas

The cost of producing biogas and upgrading it for entry into the natural gas net, is based on calculations carried out for the Biogas taskforce – Danish Energy Agency, and more information can be found on their website.[4] The total costs were estimated at 166 DKK/GJ. From this figure, the value of the positive socioeconomic affects were subtracted as stated in a IFRO report (Jacobsen, Laugesen, Dubgaard, & Bojesen, 2013): Increased value of fertilizer - 5 DKK/GJ, odour reduction – 8 DKK/GJ, and reduction of greenhouse gas reductions 6.7 DKK/GJ (based on CO_2 savings of 67 kg/GJ and a CO_2 price of 1000 DKK/tonne). This gives a total biogas production cost of 146.5 DKK/GJ for 2015 which was assumed to fall by 10% by 2030.

Electricity

All electricity for transport within this project is assumed to come from renewable energy sources, and as such an estimate for the long term cost of renewable electricity was used. Based on the assumptions and findings of a 2014 study (Ea Energy Analyses, 2014), the current study works with an

[4] http://www.ens.dk/undergrund-forsyning/vedvarende-energi/bioenergi/afrapportering-biogas-taskforce

assumption that in 2015 the RE price will be set via 50% onshore wind and 50% offshore wind, giving an average production cost of roughly 600 DKK/MWh. Meanwhile, the 2030 RE price is assumed to be set by a combination of 60% offshore wind and 40% solar power, resulting in a price of roughly 700 DKK/MWh. By 2030 it is also assumed that EVs will have a system value in the order of 50 DKK/MWh (i.e. via their ability to charge at times with low prices), thus bringing the RE cost utilised in 2030 to 650 DKK/MWh.

Hydrogen

Hydrogen within this project is assumed to be produced at filling stations from the 100% renewable electricity as described above. The production cost of hydrogen is based on work Ea Energy Analyses has contributed to in the Commercialisation of Hydrogen Technologies project.[5] The cost assumptions and resulting hydrogen production cost as displayed in the table below.

			2015	2020	2030
Inputs and calculations:					
	Electricity price (RE)	DKK/MWh	600	600	700
	Average price when avoiding 25% most expensive hours	%	80%	80%	75%
	Resulting electricity price	Euro/MWh	64.5	64.5	70.6
	Lifetime of plant	years	25	25	25
	Discount rate	%	4%	4%	4%
	Investment cost	M€/MWe	0.82	0.82	0.82
	Fixed O&M	€/MWe per year	50,000	50,000	50,000
	Average lifetime efficiency, electricity to heat (%)	%	64%	64%	64%
	Full load hours	hours	6,000	6,000	6,000
	Capital cost	€/Mwe	52,490	52,490	52,490
Per electricity unit					
	Capital cost	€/MWhe	8.7	8.7	8.7
	O&M	€/MWhe	8.3	8.3	8.3
	Electricity cost	€/MWhe	64.5	64.5	70.6
	Total	**€/MWhe**	**81.6**	**81.6**	**87.6**
Per H2 (lower heating value)					
	Capital cost	€/MWh H2	13.7	13.7	13.7
	O&M	€/MWh H2	13.0	13.0	13.0
	Electricity cost	€/MWh H2	100.8	100.8	110.3
	Total	**€/MWh H2**	**127.5**	**127.5**	**136.9**
	Hydrogen production cost	**DKK/GJ**	**264**	**264**	**283**

Table 7: Hydrogen production costs

[5] http://ea-energianalyse.dk/projects-english/1411_analysis_for_commercialization_of_hydrogen_technologies.html

Fuel transmission and distribution costs

Gasoline and diesel

All vehicle categories

As was the case for the production costs, gasoline and diesel transmission and distribution costs were based on those that Ea Energy Analyses provided to the Danish Energy Agency (DEA) as described above. These distribution costs included sunk costs associated with depots and other storage infrastructure. As these infrastructure items are not anticipated to be expanded during the study period, the sunk portion of these costs has been subtracted for the purposes of this study. After consultations with the Danish Oil Industry Association (EOF), it was determined that these figures equate to roughly 1.1 DKK/GJ for gasoline and diesel.

Natural gas

All vehicle categories

It is assumed that the cost of distributing natural gas to a gas station will be similar to that for a decentral heating plant. Therefore, the natural gas distribution and transmission costs for a decentral heating plant are those from the above mentioned Danish Energy Agency (DEA) study. The study does not include the 'sunk' costs associated with natural gas net, and therefore these transmission and distribution costs are quite low, in the order of 2.5 DKK/GJ.

Bioethanol and biodiesel

All vehicle categories

Bioethanol and biodiesel are assumed to be blended into gasoline and diesel at the refinery. Therefore the transmission and distribution costs for gasoline and diesel described above were used as a starting point, and then adjusted according to their energy content per litre.

Biogas

All vehicle categories

As all biogas is assumed to be upgraded and transferred to the natural gas net, the transmission and distribution cost for natural gas was used, with a small adjustment according to the energy content of biogas as related to natural gas.

Electricity

All vehicle categories

As was the case for natural gas, it is assumed that the additional demand from EVs will not require an expansion of the transmission net. As such, the marginal costs associated with electricity transmission for EVs is quite low.

In terms of the electricity distribution costs, estimates were based on a study undertaken for Energitilsynet. In 2022 it was forecasted that total OPEX costs for electricity distribution companies would be roughly 3.2 billion DKK, and total electricity use would be roughly 33 TWh (ENS, 2014). This gives a value of 100 DKK/MWh and this figure has been used through to 2030.

Hydrogen

All vehicle categories

Hydrogen is assumed to be produced locally at the individual filling stations with electricity from the distribution net. As a result, the cost associated with the distribution of hydrogen utilised in the study is based on the aforementioned electricity distribution value of 100 DKK/MWh, the estimated lower cost realised due to the hydrogen plant producing at times when electricity is in lesser demand, and the conversion efficiency of the hydrogen plant.

		2015	2020	2030
Inputs and calculations:				
Electricity distribution cost	DKK/MWh	100	100	100
Average price when avoiding 25% most congested hours	%	80%	80%	75%
Average lifetime efficiency, electricity to heat (%)	%	64%	64%	64%
Hydrogen distribution cost	**DKK/GJ**	**35**	**35**	**33**

Table 8: Hydrogen distribution costs

Fuel infrastructure costs

For some of the fuels, the cost of the filling infrastructure is included in the distribution and transmission costs, while for other it is not, and it therefore requires an additional calculation as described below.

Gasoline, diesel, bioethanol and biodiesel

All vehicle categories

For all four of these fuels, the cost of the filling station is included in the distribution and transmission cost, as the DEA study does not distinguish between the two.[6]

Natural gas

To estimate the filling costs for natural gas, a bottom up analysis was undertaken by Dansk Energi. Ea Energy Analyses has adopted part of this methodology and made some alterations and modifications to suit the aspects of the current project. The primary data source was the DEA's report entitled "Rammevilkyear for gas til tung vejtransport" (COWI, 2014).

An expected life of 20 years, and a discount rate of 4% were used. The analysis inputs included estimates of:

- CAPEX and OPEX for 3 types of filling options, including the cost of connecting the station to an existing natural gas line:
    - Home fuelling
    - A small petrol station
    - A large petrol station
- The number of natural gas stations estimated to be in operation for a given year. For each year this is the greater of:
    a. The number of natural gas stations that have been confirmed will be in operation in any given year. In 2015, there are for example 10 natural gas stations in Denmark, and according to gasbiler.info, roughly one to two per will be added in the next few years (Gasbiler.info, 2015).
    b. The minimum number of each type of station required to fulfil the estimated demand for natural gas/biogas. As such, in contrast to 2015 when the minimum is set by the number of announced gas stations (10), in 2030, when natural gas/biogas demand increases substantially, the total number of stations required is based on

[6] For biodiesel and bioethanol, roughly 1 DKK/GJ was added to cover the costs of additional pumps associated with an additional gasoline/diesel blend.

the overall gas demand and the estimated capacity of each station type (ca. 40).

- The estimated maximum utilisation rate of each station type in each year. As the gas demand increases it is expected that the average utilisation rate of stations will also increase as each station will cover a smaller geographic area.

The above methodology results in a very high DKK/GJ cost in the initial years, as the utilisation rate of the stations is very low. In 2015 for example, only 40 TJ of natural gas for transport are spread out over 10 stations, giving a utilisation rate of under 20%. Meanwhile in 2030 for example, annual utilisation rates are expected to be closer to 80%.

The resulting costs for each station type in DKK/GJ are displayed below:

Filling station type	Costs (DKK/GJ)		
	2015	2020	2035
Home fuelling	71	73	80
Small petrol station	138	125	26
Large petrol station	74	23	14

Table 9: Infrastructure costs for natural gas based on filling station type and year (2015 DKK/GJ)

For the years in between the intervals above, a simple linear extrapolation was done, thus resulting in costs for the relevant years from 2015-2030[7]. The reason for the much higher costs for the small petrol stations in 2015 and 2030 is due to the assumption that the majority of filling stations currently being built will be small, and therefore they will be largely underutilised until well after 2020. In this regard, it is important to note that the above 'socioeconomic' costs are not anticipated to necessarily be reflected in the cost the consumer pays at the respective stations. I.e. in 2020 the high cost associated with small stations is due to the low utilisation rate, but it is highly unlikely that the station operator can pass these costs directly to the consumer.

Personal vehicles

For each vehicle type, a weighted average was undertaken according to the assumed amount of filling that would be undertaken from each filling station type. Combined with the costs displayed in Table 9, the resulting costs are given below.

[7] The tables in this section display the year 2035 instead of 2030 as Dansk Energi uses the year 2035.

Filling station type	Filling by station type (%)		
	2015	2020	2035
Home fuelling	5	3	1
Small petrol station	95	62	54
Large petrol station	-	35	45
Resulting average cost (DKK/GJ)	**135**	**88**	**21**

Table 10: Infrastructure costs for natural gas for personal vehicles, based on assumed usage of each station type.

Here it is assumed that as a greater number of large filling stations become available, a growing number of personal vehicle owners will utilise the large stations, which are likely to have lower prices.

Light duty vehicles

Combined with the costs displayed in Table 9, the resulting costs for LDVs are given below.

Filling station type	Filling by station type (%)		
	2015	2020	2035
Home fuelling	1	1	1
Small petrol station	85	55	42
Large petrol station	14	44	57
Resulting average cost (DKK/GJ)	**128**	**80**	**19**

Table 11: Infrastructure costs for natural gas for LDVs, based on assumed usage of each station type.

For LDVs it is assumed that very few will tank at home, and once again, as a greater number of large filling stations become available they will become the first choice.

Heavy duty vehicles & busses

Combined with the costs displayed in Table 9, the resulting costs for HDVs and busses are given below.

Filling station type	Filling by station type (%)		
	2015	2020	2035
Home fuelling	-	-	-
Small petrol station	75	40	25
Large petrol station	25	60	75
Resulting average cost (DKK/GJ)	**122**	**64**	**17**

Table 12: Infrastructure costs for natural gas for HDVs and busses, based on assumed usage of each station type.

HDVs and busses are not assumed to fill at home, and are most likely to rely on large petrol stations to the greatest extent possible.

Biogas

All vehicle categories

As all biogas is assumed to be upgraded and transferred to the natural gas net, the infrastructure cost for natural gas is used, with a small adjustment according to the energy content of biogas as related to natural gas.

Electricity

Similar to natural gas, electricity infrastructure costs took their point of departure in a bottom up analysis undertaken by Dansk Energi. Ea Energy Analyses has again adopted this methodology and made slight alterations and modifications. The primary data source was the DEA's report entitled "Redegørelse om rammebetingelser for opstilling af ladestationer til elbiler Infrastruktur for ladestandere til elbiler i det "offentlige rum"[8], from January of 2011.

Once again, an expected life of 20 years, and a discount rate of 4% were used. The analysis inputs included estimates of:

- CAPEX and OPEX for 3 types of charging:
    - Home charging
    - Public charging
    - Public rapid charging
- Estimates for the utilisation rate of each type of public station from now to 2035 for each vehicle category are displayed below. For personal vehicle home charging, the utilisation rate is simply based on the % of charging assumed to be done at home, and the assumed total annual required amount of charging. Again, it is assumed that utilisation rates will grow as an increasing number of battery reliant vehicles make their way on to the Danish roads.

Vehicle category & charger station type	Utilisation rate (%)		
	2015	2020	2035
Personal vehicle – public charger	5	15	30
Personal vehicle – public rapid charger	5	15	30
LDV – public charger	18	33	45
LDV – public rapid charger	18	33	45
Busses – public charger	30	50	60
Busses – public rapid charger	30	50	60

Table 13: Assumed utilisation rates according to vehicle category and charger station type.

[8] http://www.ens.dk/sites/ens.dk/files/info/nyheder/nyhedsarkiv/arbejdsgruppe-giver-bud-paa-udrulningsplan-ladestandere-elbiler/Redeg_ladestandere_elbiler_jan2011_final.pdf

Based on the above utilisation rates, and the assumed CAPEX and OPEX inputs, the following table displays the resulting costs per charging station according to vehicle category.

Vehicle category & charger station type	DKK/GJ		
	2015	2020	2035
Personal vehicle – home charger	66	76[9]	62
Personal vehicle – public charger	270	88	16
Personal vehicle – public rapid charger	593	158	22
LDV – public charger	77	41	11
LDV – public rapid charger	170	73	14
Busses – charger	45	26	8
Busses – rapid charger	99	47	11

Table 14: Resulting costs per charging station according to vehicle category

As can clearly be seen in the table, the assumed utilisation rate is a dominant determining factor in the resulting infrastructure cost. As for other fuels, for the years in between the intervals above, a simple linear extrapolation was done.

Personal vehicles

As was the case for natural gas, for each vehicle type, a weighted average was undertaken according to the assumed amount of charging that would be undertaken from each charging type. Combined with the costs displayed in Table 14, the resulting costs are given below.

Charger type	Charing by type (%)		
	2015	2020	2035
Home charging	75	75	75
Public charging	15	15	15
Public rapid charging	10	10	10
Resulting average cost (DKK/GJ)	**149**	**86**	**51**

Table 15: Infrastructure costs for electricity for personal vehicles, based on assumed usage of each charger type.

Here it is assumed that the vast majority of charging will take place at home, with this dispersion not changing over the scenario period.

Light duty vehicles

Combined with the costs displayed in Table 14, the resulting costs for LDVs are given below.

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[9] The reason for this cost increase from 2020 to 2015 is that despite the charger becoming cheaper, the EV is now more efficient, and thereby uses less energy. Therefore, on a per GJ basis, the infrastructure cost increases.

Charger type	Charing by type (%)		
	2015	2020	2035
Home charging	10	5	5
Public charging	40	50	60
Public rapid charging	50	45	35
Resulting average cost (DKK/GJ)	**122**	**57**	**15**

Table 16: Infrastructure costs for electricity for LDVs, based on assumed usage of each charger type.

For LDVs it is assumed that very few will charge at home, and as the battery size and driving range increase, less rapid charging will be required.

Busses

Combined with the costs displayed in Table 14, the resulting costs for busses are given below.

Charger type	Charing by type (%)		
	2015	2020	2035
Home charging	-	-	-
Public charging	40	50	60
Public rapid charging	60	50	40
Resulting average cost (DKK/GJ)	**77**	**37**	**9**

Table 17: Infrastructure costs for electricity for busses, based on assumed usage of each charger type.

Busses are not assumed to charge at home, and like LDVs, will likely try to reduce their reliance on rapid charging as their driving range increases.

Hydrogen

All vehicle categories

Hydrogen is not utilised in any of the scenarios, and therefore infrastructure costs have not been thoroughly investigated. Due to the lack of hydrogen vehicles on Danish roads today, any current filling station would have an extremely low utilisation rate, thereby resulting in a particularly high per GJ cost. It has been conservatively estimated that on a per GJ basis, infrastructure costs today would be 5 times higher for hydrogen relative to electricity, with this figure falling to double by 2030, under the assumption that utilisation rates improve quite substantially for hydrogen stations. It should be noted that these figures are somewhat lower than the figures Dansk Energi have arrived at in their analysis.

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